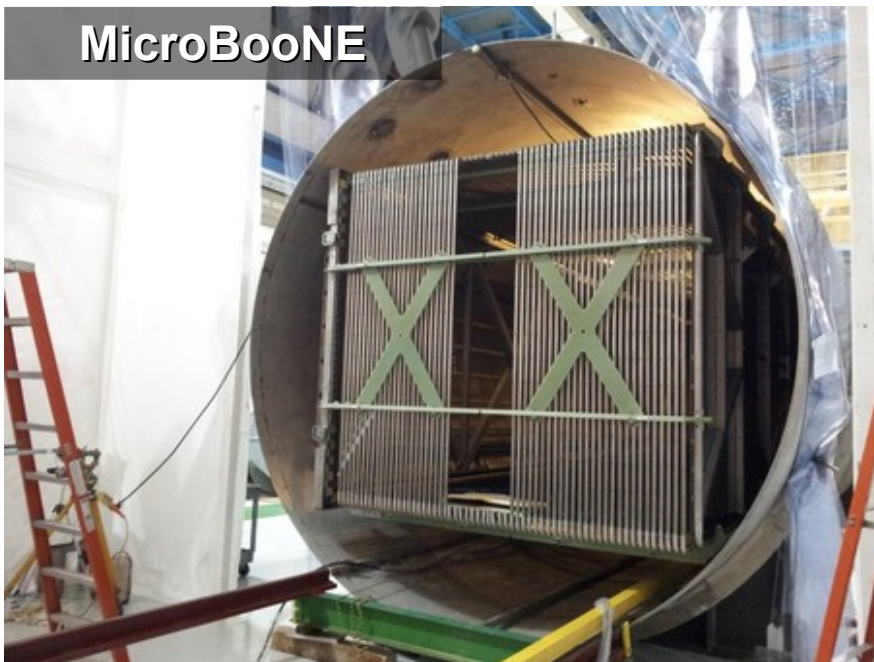
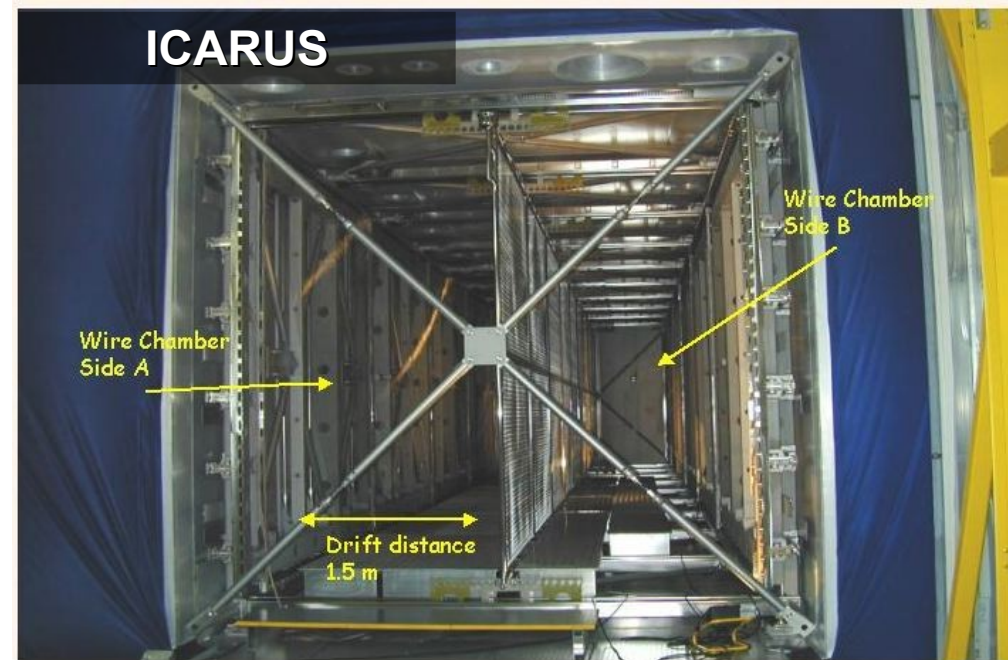


MicroBooNE



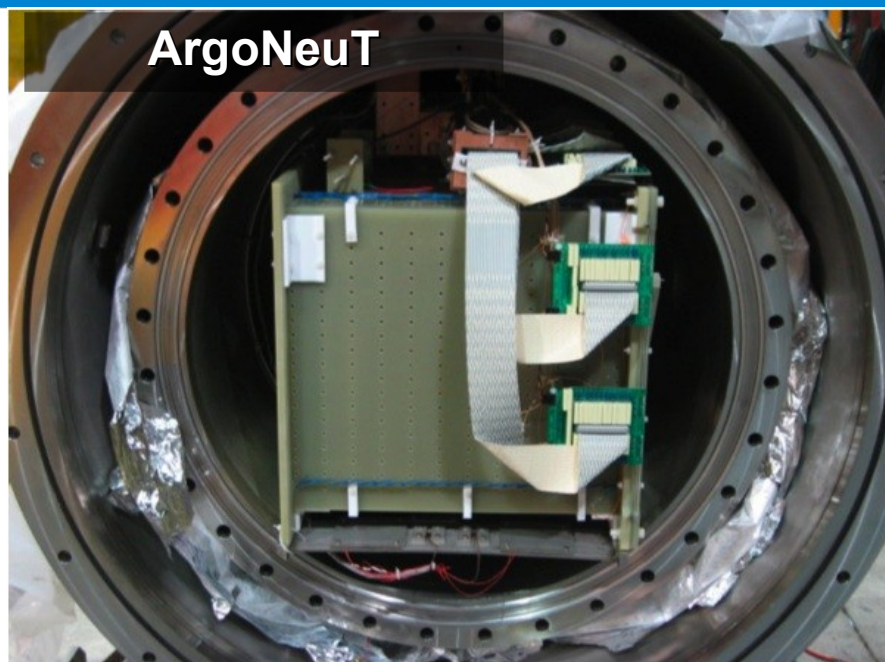
ICARUS



Liquid Argon Time Projection Chambers (LArTPC's)

Jonathan Asaadi (Syracuse University)

ArgoNeuT



Bo



Long Bo

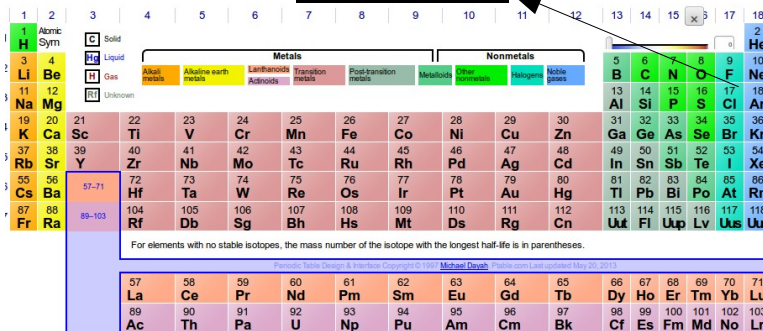


When I was thinking about the subject material and title of this talk, I kept coming back to this breakdown of the words

Liquid Argon Time Projection Chambers

Yup, know what that is

Ar



Periodic table of elements showing the liquid state of Argon (Ar) and the time projection chamber (TPC) technology.

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Periodic Table Design & Interface Copyright © 1999 Michael Deane. Website last updated May 20, 2013.

Got it, I can Wikipedia that information



Hmmm...this one maybe isn't so clear

But, before launching in to a discussion of what this technology is and why these words are in the title of my talk, I thought I might try to answer a slightly bigger question first...

What is it we are trying to study using these detectors?

Particle Physics

The Standard Model

Specifically we want to study the basic “ingredients” of what makes up the universe around us.

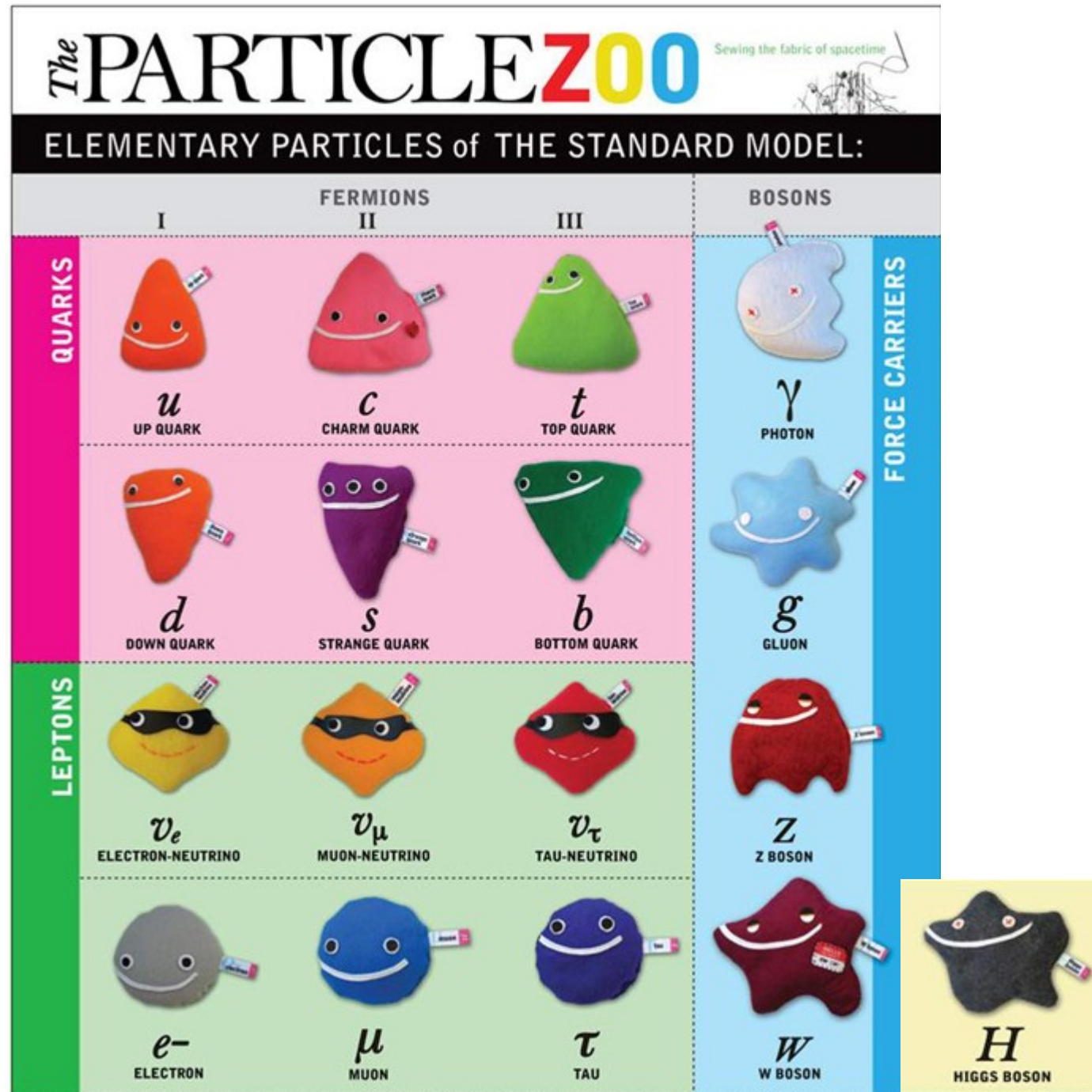
So we come up with questions like:

- What are the basic ingredients of matter?

- How do these ingredients interact with each other?

- Are these ingredients 'fundamental'?


















So on and so on...



Particle Physics

Just as a quick refresher:

You, me, and pretty much everything else you will ever see in the universe is made of these things (Protons, neutrons, electrons)

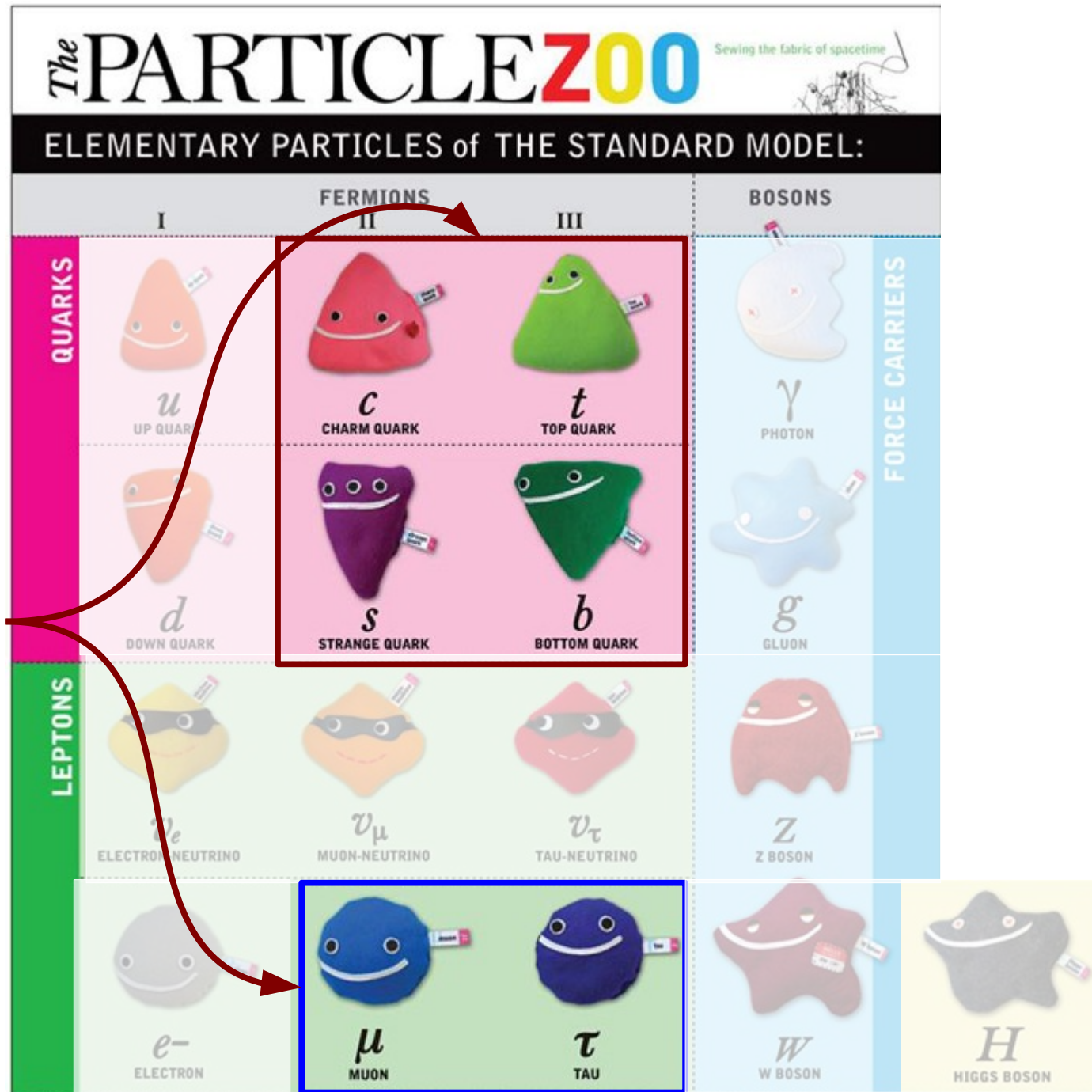
| The PARTICLE ZOO <small>Sewing the fabric of spacetime</small> | | | | |
|--|--|---|---|---|
| ELEMENTARY PARTICLES of THE STANDARD MODEL: | | | | |
| | I | II | III | BOSONS |
| QUARKS |  u UP QUARK |  c CHARM QUARK |  t TOP QUARK |  γ PHOTON |
| |  d DOWN QUARK |  s STRANGE QUARK |  b BOTTOM QUARK |  g GLUON |
| LEPTONS |  ν_e ELECTRON-NEUTRINO |  ν_μ MUON-NEUTRINO |  ν_τ TAU-NEUTRINO |  Z Z BOSON |
| |  e^- ELECTRON |  μ MUON |  τ TAU |  W W BOSON |
| | | | |  H HIGGS BOSON |

Particle Physics

Just as a quick refresher:

You, me, and pretty much everything else you will ever see in the universe is made of these things (Protons, neutrons, electrons)

These other particles exist in very energetic environments (think particle colliders), but quickly change into (decay to) the stuff we are made of...



Particle Physics

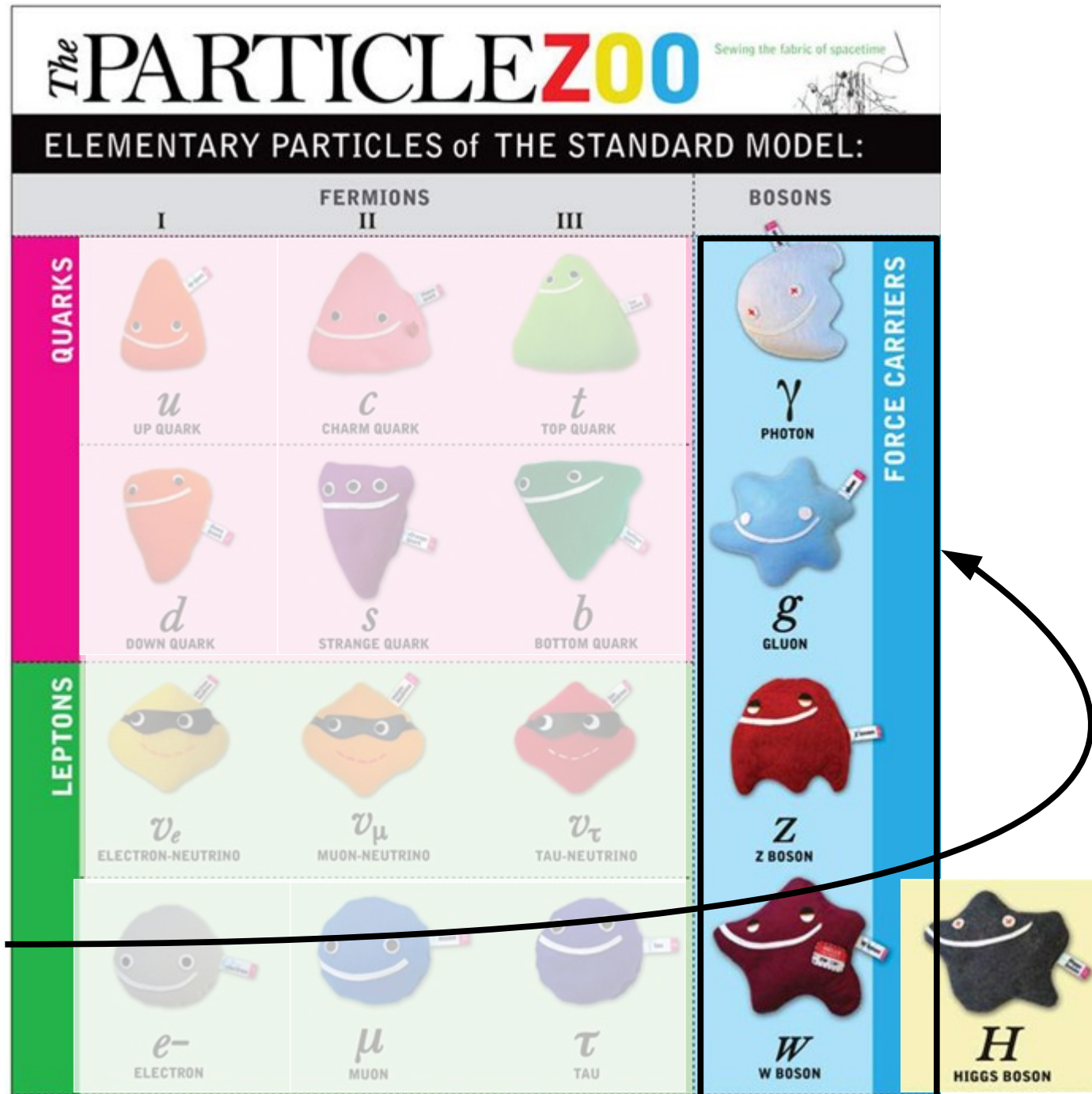
Just as a quick refresher:

You, me, and pretty much everything else you will ever see in the universe is made of these things (Protons, neutrons, electrons)

These other particles exist in very energetic environments (think particle colliders), but quickly change into (decay to) the stuff we are made of...

These particles describe how all the other particles “talk” to each other (through different forces)

(and for now we skip over the Higgs and what it does)



What about the neutrinos?

Turns out that these “forgotten” about particles are extremely interesting!

How interesting you ask...?

Well, in addition to being 3 of only a handful of fundamental point-like particles known to exist...

(as if that isn't enough)



Neutrinos



The Particle Universe

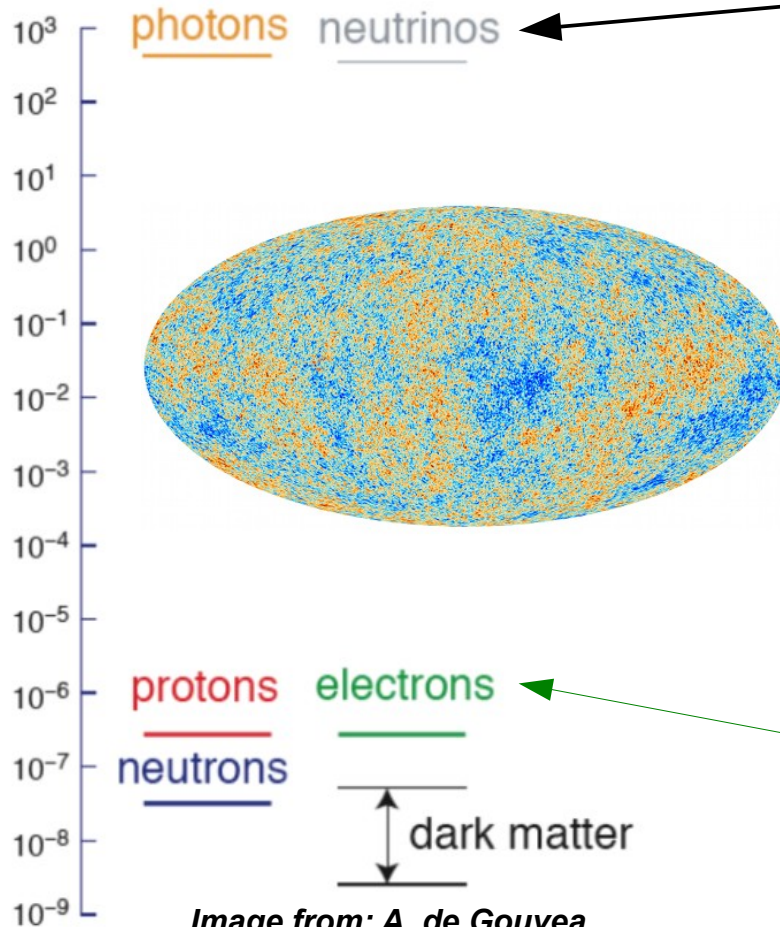
1) They are the second most abundant particle in the entire universe!

Neutrinos are a relic of the big bang

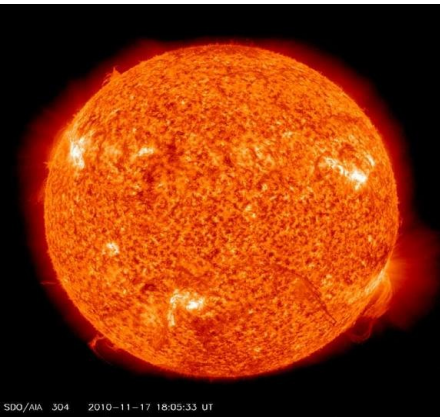
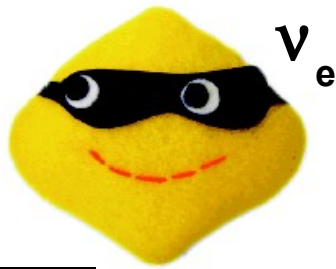
(~ 100 billion neutrinos go through your thumb every second)

n.b. I stole this fact wholesale from a talk by a noted neutrino theorist so it comes with no warranty

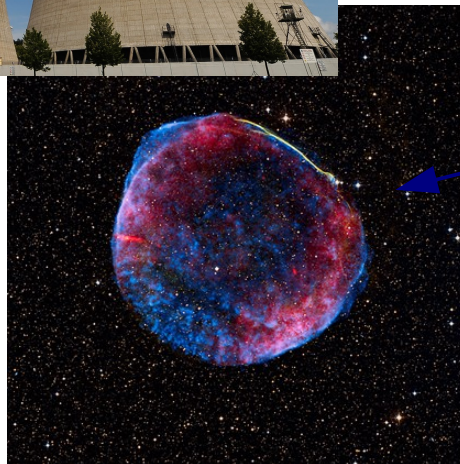
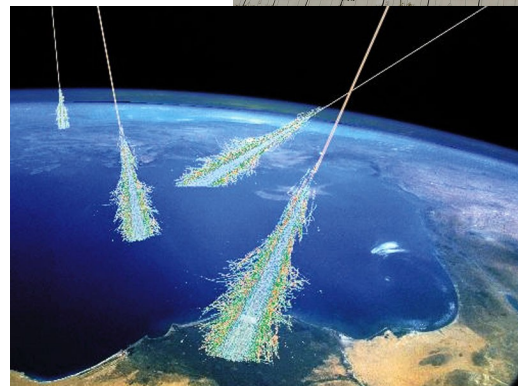
Way more abundant than all the stuff you will ever interact with on this planet (or for that matter any planet)



Neutrinos



2) They are produced in copious amounts in both natural and man made processes (things involving radiation)



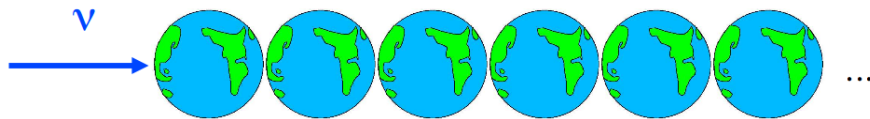
In fact ~ 100 times more energy is released from neutrinos in a supernova burst than in any other form

n.b. I stole this fact wholesale from a talk by a noted neutrino theorist so it comes with no warranty

Neutrinos



Image from: B. Flemming



A neutrino could travel through ~200 earths before interacting at all!

3) Neutrinos are very, very, very weakly interacting!

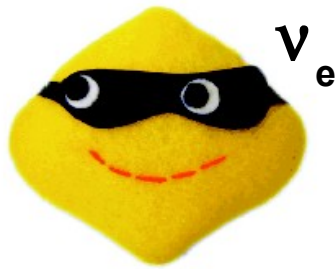


You would need a lead wall the thickness of the solar system to stop neutrinos from the sun

Neutrinos only interact via the weak nuclear force ($W^{+/-}$, Z^0) and they carry no electric charge (electrically neutral)

**And...as recently as 1998 neutrinos were thought to have no mass¹⁰
But nature had a surprise for us...**

Neutrinos



Turns out that we observe neutrinos changing (oscillating) their type (flavor)

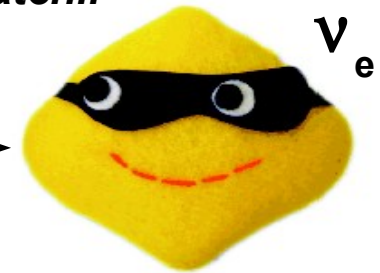
The details of how we observed this we can talk about later...



*This means I can
start with one type of
neutrino*



*Let it travel some
distance*



*And it will have
changed its type*



**The only way this
can happen is if
neutrinos have
mass**

*(flavor eigenstates are
linear combinations of
the mass eigenstates)*

Ok, Ok...neutrinos are interesting...now what?

So now we've established that neutrinos are interesting and we'd like to study them in detail in hopes of gaining insight into the universe...how do we do it?

Two important properties to keep in mind:

1) Neutrinos are very, very, very weakly interacting

2) They are “easy” to produce in copious amounts

So one good strategy to detecting neutrinos is to produce a whole lot of them in a well defined area and then put something very dense, very big and very sensitive to neutrino interactions

Simplified neutrino interactions

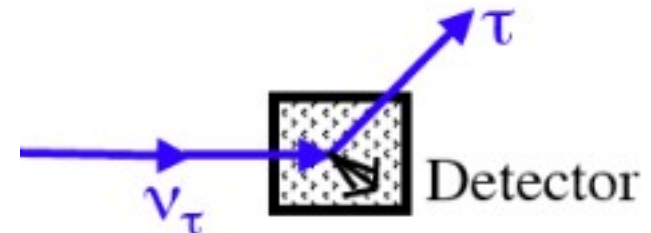
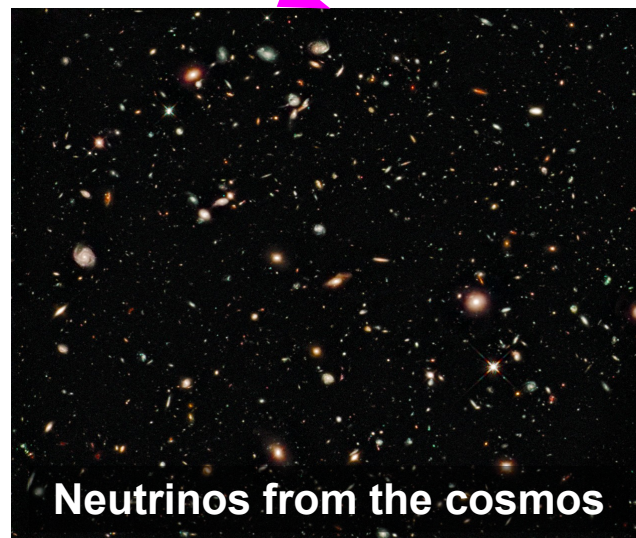
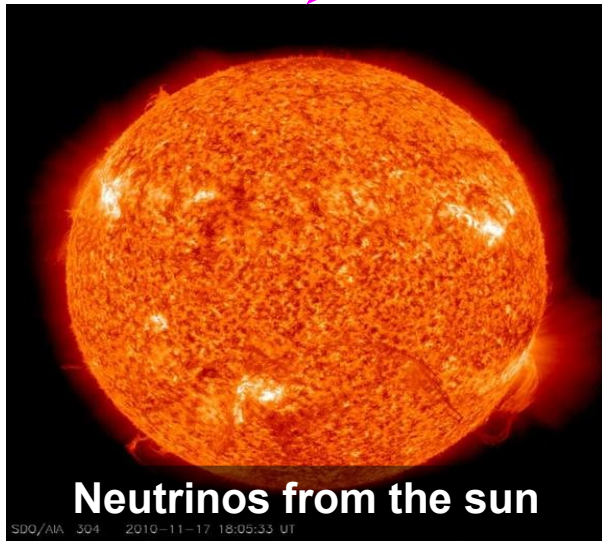


Image from: A. de Gouvea

Producing Neutrinos

So one good strategy to detecting neutrinos is to produce a whole lot of them in a well defined area and then put something very dense, very big, and very sensitive to neutrino interactions



All of these sources produce an abundance of neutrinos and are utilized in many experiments

(Note: The choice for your source of neutrinos also guides your choice in what type of detector you use)

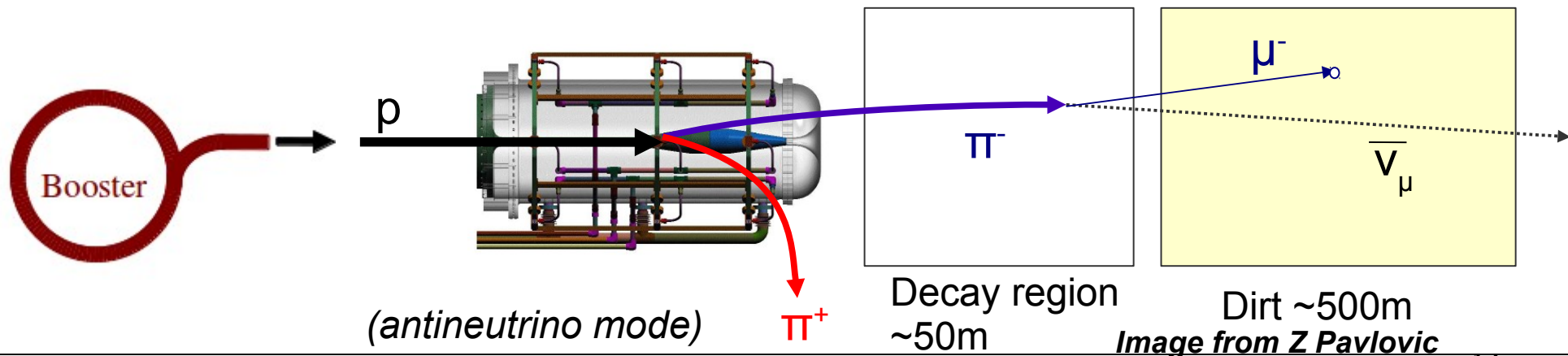
For our discussion we will focus on the way we produce neutrinos here at Fermilab

Namely, via a **particle accelerator**

Producing Neutrinos

Video produced by **Symmetry magazine** explaining how we make a beam of neutrinos

http://www.youtube.com/watch?feature=player_detailpage&v=U_xWDWKq1CM



So that is how we make them...what about detecting them?

Detecting Neutrinos

So one good strategy to detecting neutrinos is to produce a whole lot of them in a well defined area and then put something very dense, very big, and very sensitive to neutrino interactions



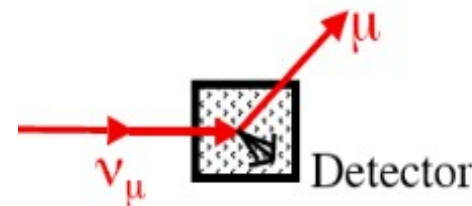
Dense

(You don't get much more dense than steel)



Big

(Difficult to get too much bigger...heavy and expensive)



Sensitive

(Limited granularity and detail of the interaction)

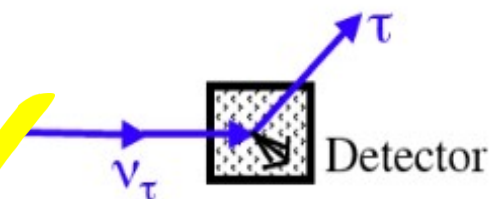
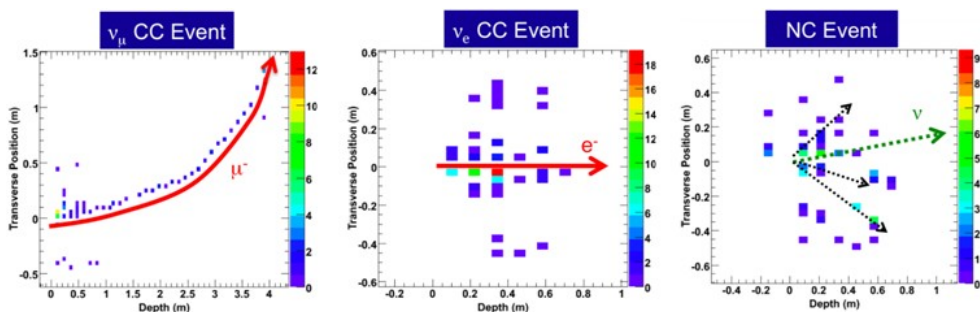


Image from: A. de Gouvea

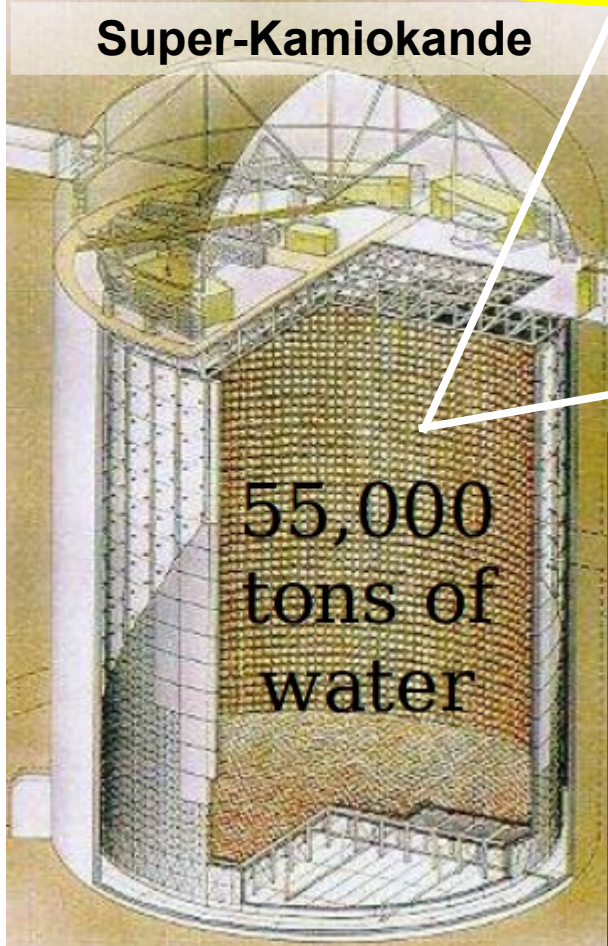


Steel scintillator

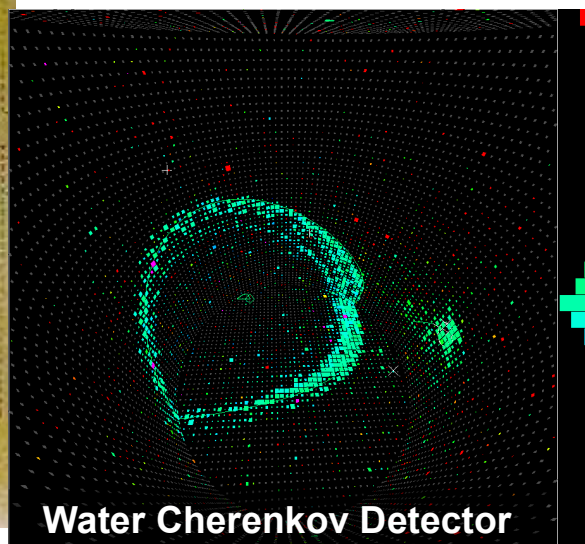
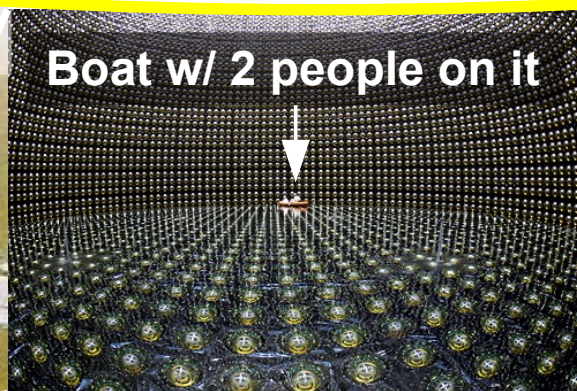
Detecting Neutrinos

So one good strategy to detecting neutrinos is to produce a whole lot of them in a well defined area and then put something very dense, very big, and very sensitive to neutrino interactions

Super-Kamiokande



Boat w/ 2 people on it



Water Cherenkov Detector

Dense

(Not the most dense thing we've got)



Big

(The detector scales to larger sizes "easily"...water is cheap)



Sensitive

(Known detector technology and quite good at seeing interactions...but again limited granularity)

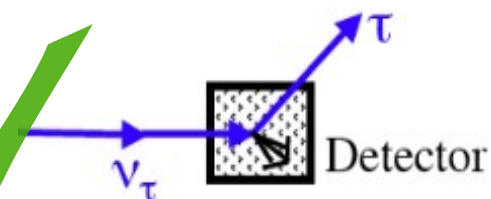


Image from: A. de Gouvea

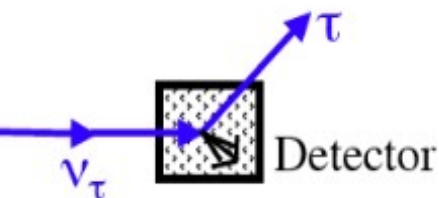
Is there another liquid we could use that is more dense, cheap, and very sensitive?

Detecting Neutrinos

Remember, what we are trying to observe is the neutrinos interaction with a nuclei (only interacts via the weak nuclear force)

→ So what we are trying to see is the positively and negatively charged particles that are produced when a neutrino interacts with a nuclei

→ Therefore, what we want is a **dense**, uniform liquid that that **ionizes easily** (high electron mobility), that **electrons once liberated won't reattach** (long electron drift), and that is **easy to produce** or already exists in great abundance (keeps the detectors cheap)



| | | | | | | | | | | | | | | | | | |
|-------------------------|----------|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|-----------|------------|------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 1 H Atomic Sym | | | | | | | | | | | | | | | | 2 He | |
| 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 55 Cs | 56 Ba | 57-71 La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 87 Fr | 88 Ra | 89-103 Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Cn | 113 Nh | 114 Fl | 115 Uup | 116 Lv | 117 Uus | 118 Uuo |

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Periodic Table Design & Interface Copyright © 1997 Michael Davah. Table.com Last updated May 20, 2013

The noble gases seem like a very good place to look

The other noble elements just don't measure up

| | He | Ne | Ar | Kr | Xe | Water |
|--------------------------------|--------|--------|--------|--------|--------|-------|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [g/cm ³] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |
| Scintillation [γ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation λ [nm] | 80 | 78 | 128 | 150 | 175 | |

Helium isn't very dense, requires very cold temps to stay liquid, and doesn't ionize well

Neon has poor electron mobility and requires very cold temps to stay liquid

Krypton is not very abundant (1 ppm in the atmosphere) nor does it produce as much scintillation light

Xenon is even less abundant (87 ppb in the atmosphere)

Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

Finally, getting back to Liquid Argon!

| | He | Ne | Ar | Kr | Xe | Water |
|--------------------------------|--------|--------|--------|--------|--------|-------|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [g/cm ³] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
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| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |
| Scintillation [γ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation λ [nm] | 80 | 78 | 128 | 150 | 175 | |

Argon is more dense than water and can be kept in the liquid phase more easily

Argon is relatively abundant (3.5 ppm in the atmosphere...or about 1% of the earth's atmosphere) more than CO₂

Argon ionizes easily (55,000 electrons / cm) and has a high electron mobility (it's greek name means lazy)

Argon produces lots of scintillation light! (Added bonus...it is transparent to the light it produces)

Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

Liquid Argon!

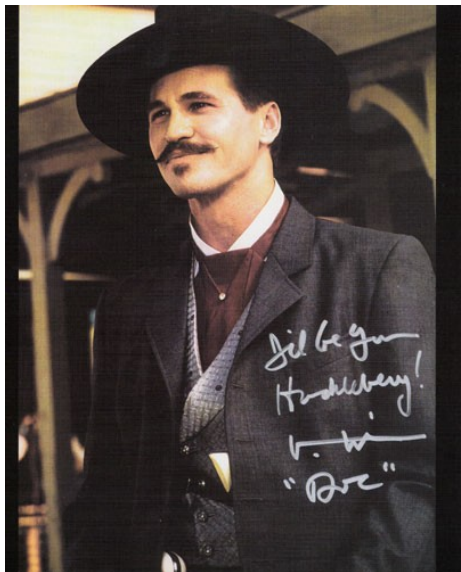


- **High Density**
- **Sensitive to neutrino interactions**
(High Ionization and Scintillation Light)
- **Homogeneous**
- **Can be built large**

(Argon is cheap and abundant...and actually we are in the business of proving that we can scale this technology...all signs look good)

It would seem that “we've found our huckleberry” in terms of a material to build a neutrino detector out of and we know how to make a beam of neutrinos!

Now, how to take all of these great properties of Liquid Argon (LAr) and turn them into a great detector

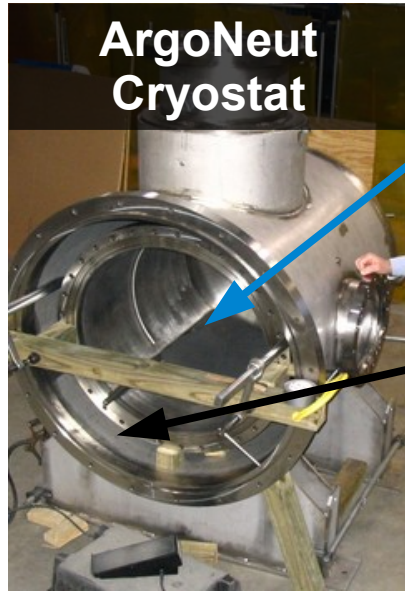


Cryostat



First off Liquid Argon has to be kept below 87 Kelvin, so you can't just put it in any old pot!

You need a vessel that is insulated to keep the Argon cold!



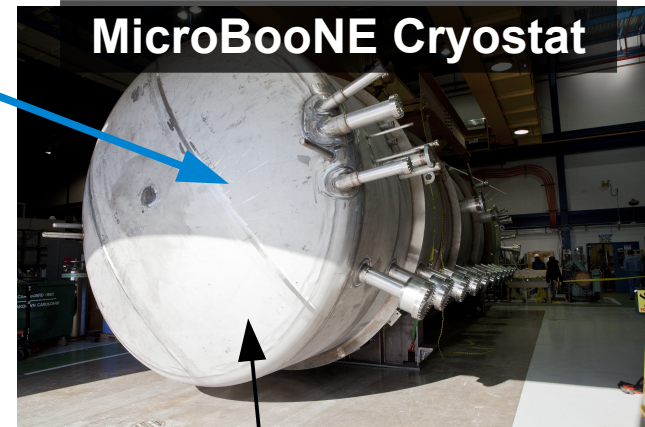
ArgoNeut Cryostat

Liquid Argon in the inner cryostat

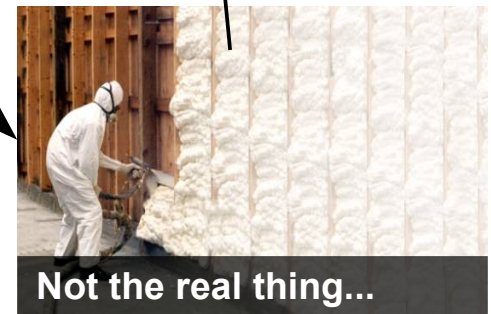
Vacuum between the inner and outer cryostat acts like an insulator

Liquid Argon inside the cryostat

Then we spray the outside with insulating foam ~6" thick



MicroBooNE Cryostat

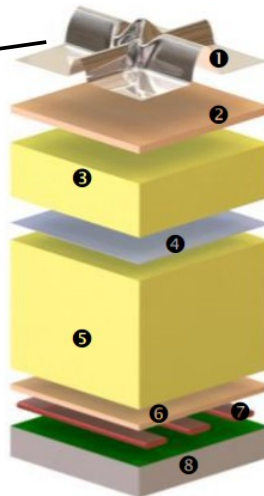


Not the real thing...



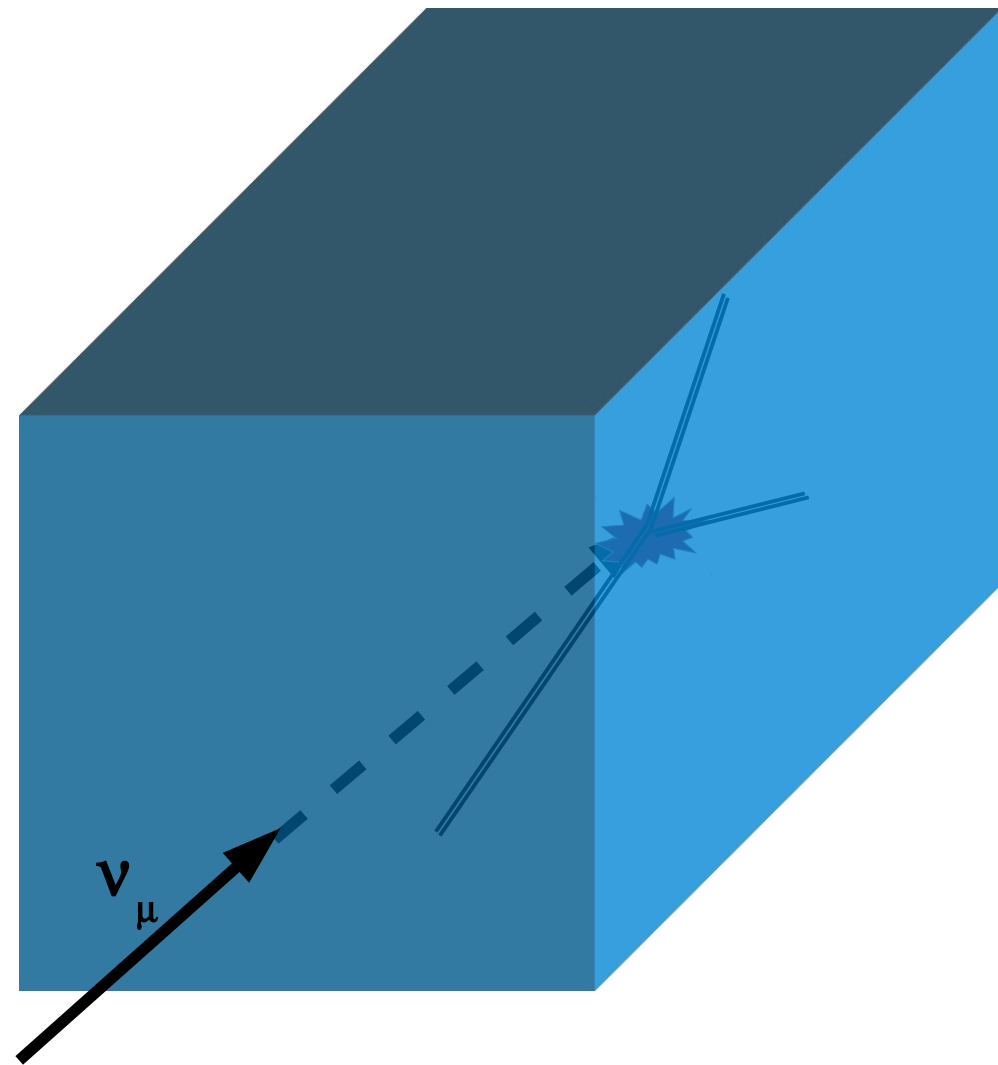
Membrane Cryostat

LNG tanker with Membrane from GTT



- 1) Stainless steel primary membrane (LAr inside here)
- 2) Plywood board
- 3) Polyurethane foam
- 4) Secondary barrier
- 5) Polyurethane foam
- 6) Plywood board
- 7) Bearing mastic
- 8) Concrete

Building the detector



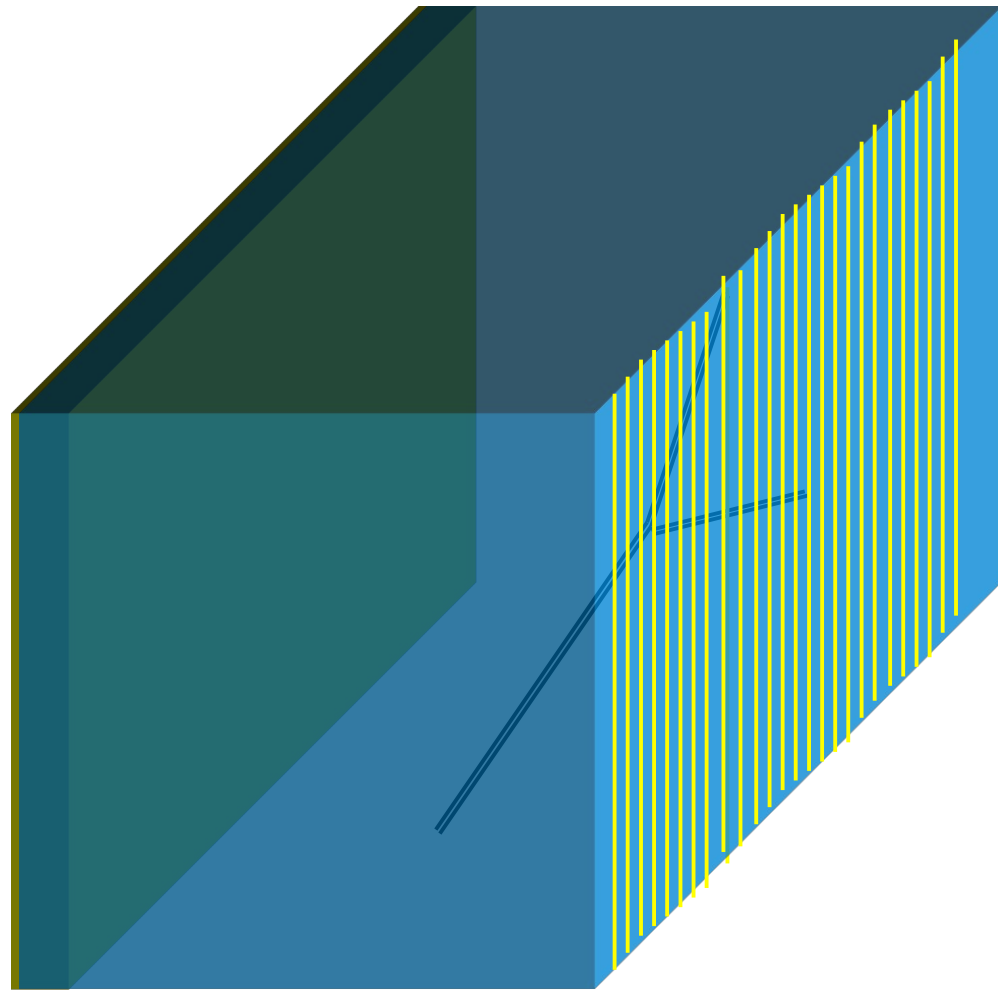
So we've got our liquid argon and got it inside a cryostat. We aim our beam of neutrinos at it...

And sure enough we have a neutrino hit an argon atom (we have an interaction)

Great! The charged particles that come out of the interaction ionize the liquid argon just like we hoped...

Only there is a problem, how do we get the ionization read out?

Building the detector



Easy enough, we just apply a **very uniform electric field** on one side and put a **bunch of wires** on the other side and look at what drifts over!

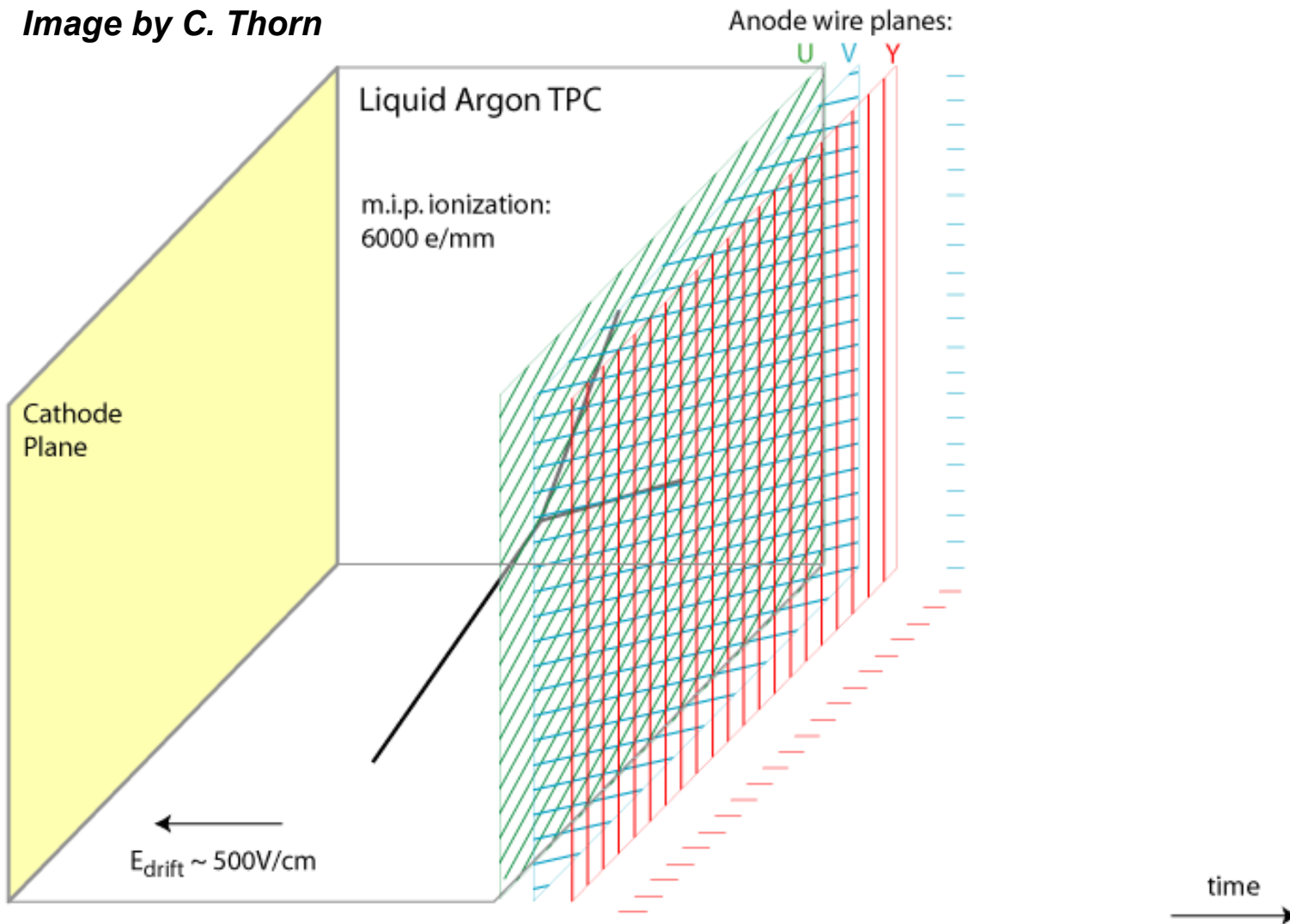
Only I don't just put one set of wires (actually I just didn't want to draw them all) you put many sets of wires at different angles

What you are reading out of your wires is the drift time of the ionization “projected” back into the volume of liquid argon

Hence a
Liquid Argon Time Projection Chamber

Liquid Argon Time Projection Chamber

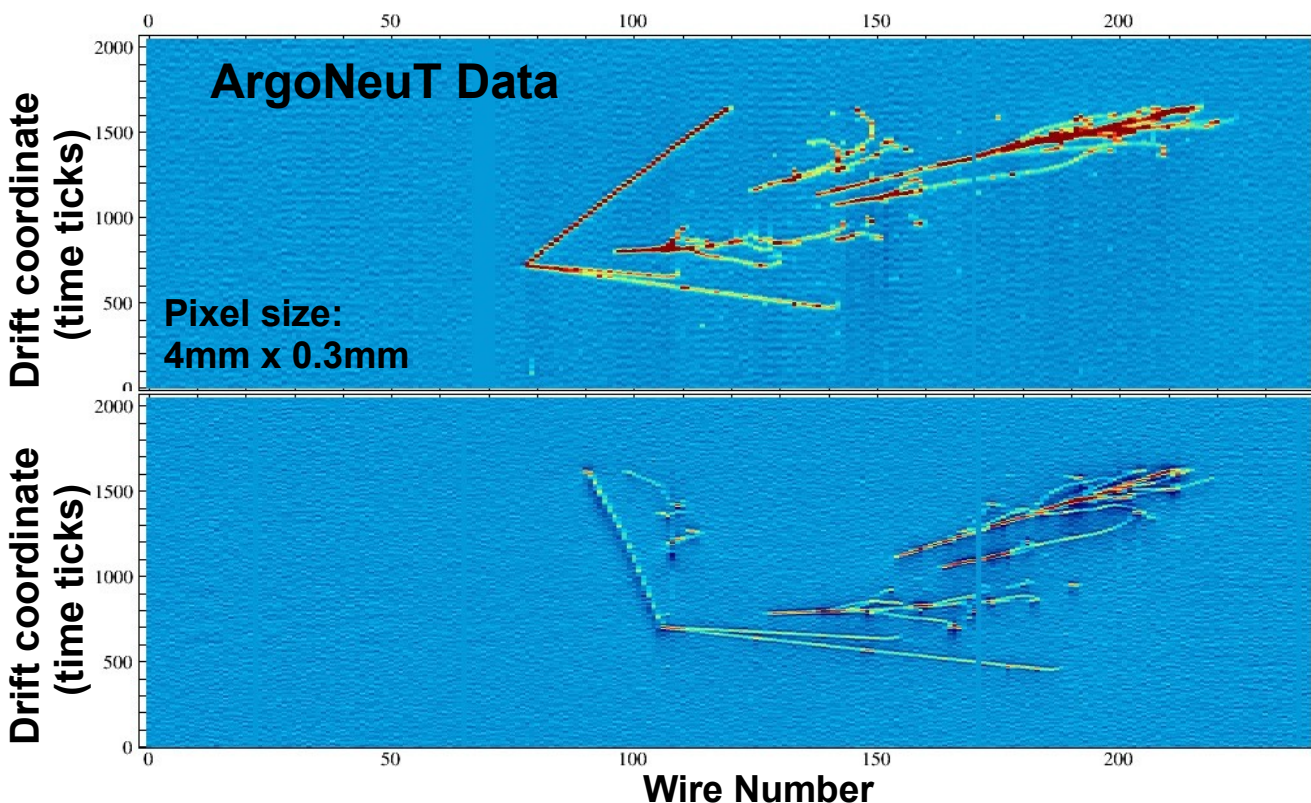
Image by C. Thorn



The wires placed at the end of the drift “sense” the ionization charge as it goes past the wires and gives a 2-d view of the event

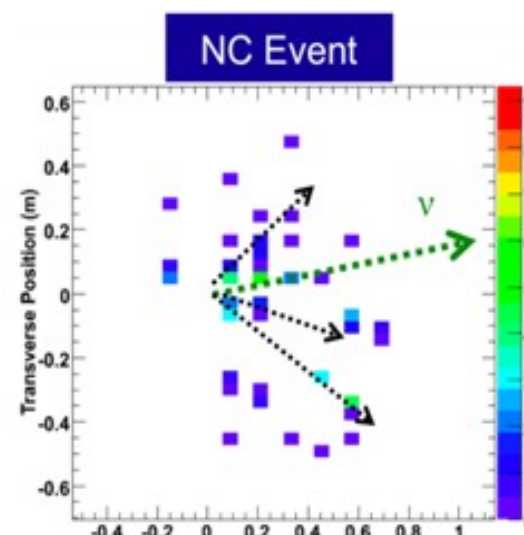
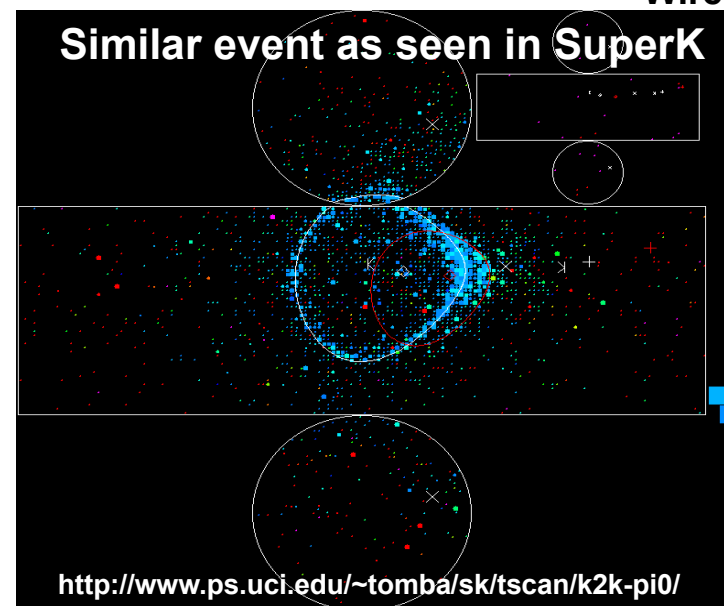
Using multiple wire planes with different angles allows us to perform 3-d event reconstruction!

Liquid Argon Time Projection Chamber



**Amazing
granularity and
detail seen in the
detector**

Similar event as seen in SuperK



Similar event seen in MINOS

Great! So we done here?

Well not quite...

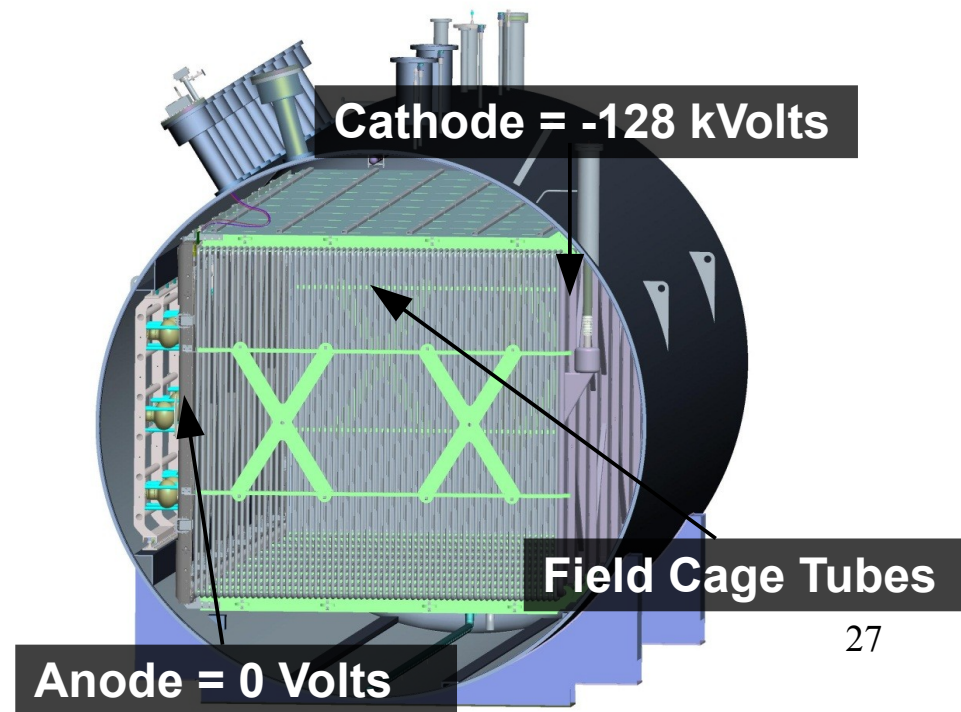
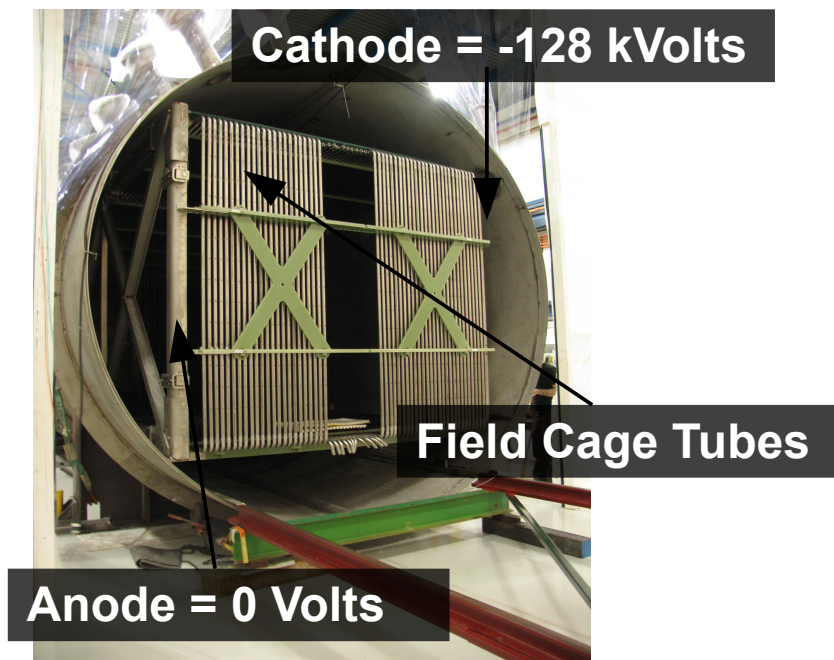
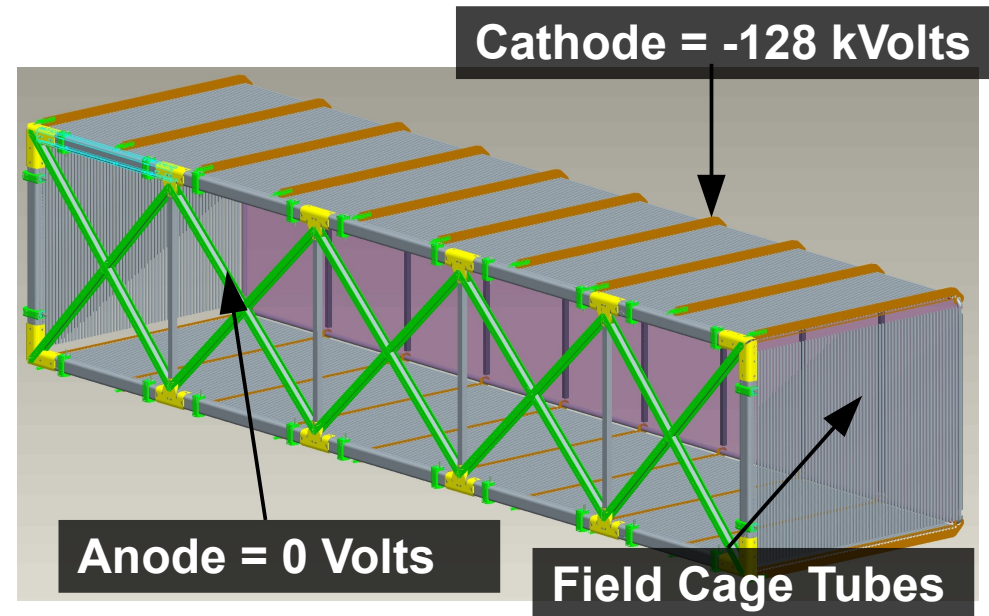
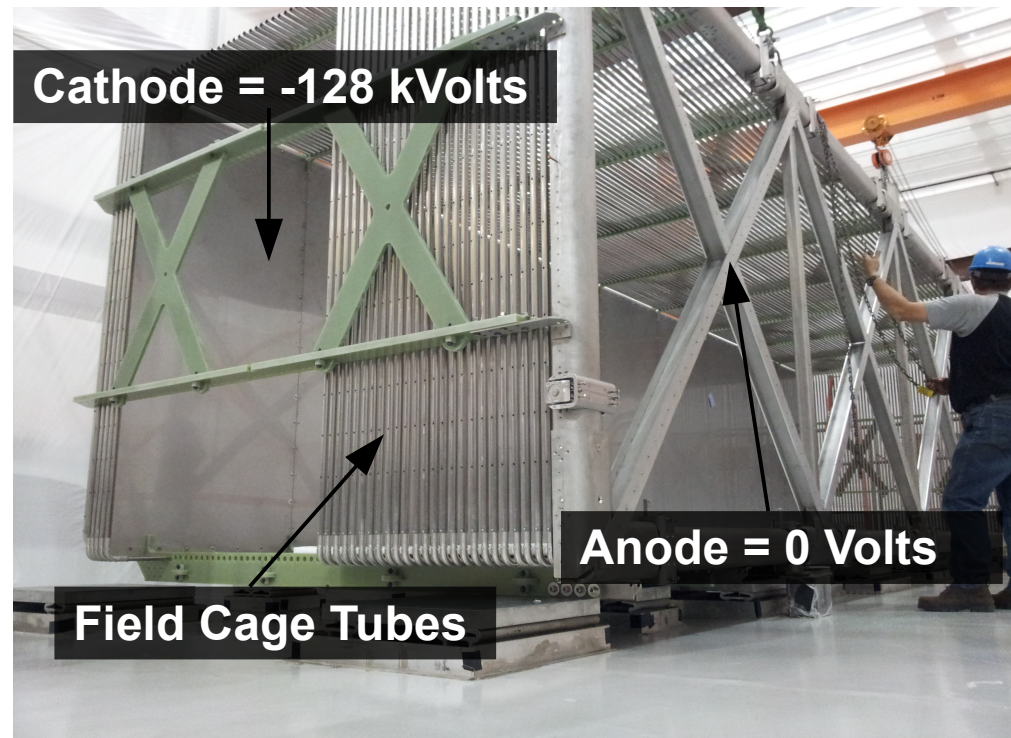
So I kinda cheated in my description of drifting the charge over to the wires...

I said “**need to apply a very uniform electric field**” but didn't actually say what I meant by that...

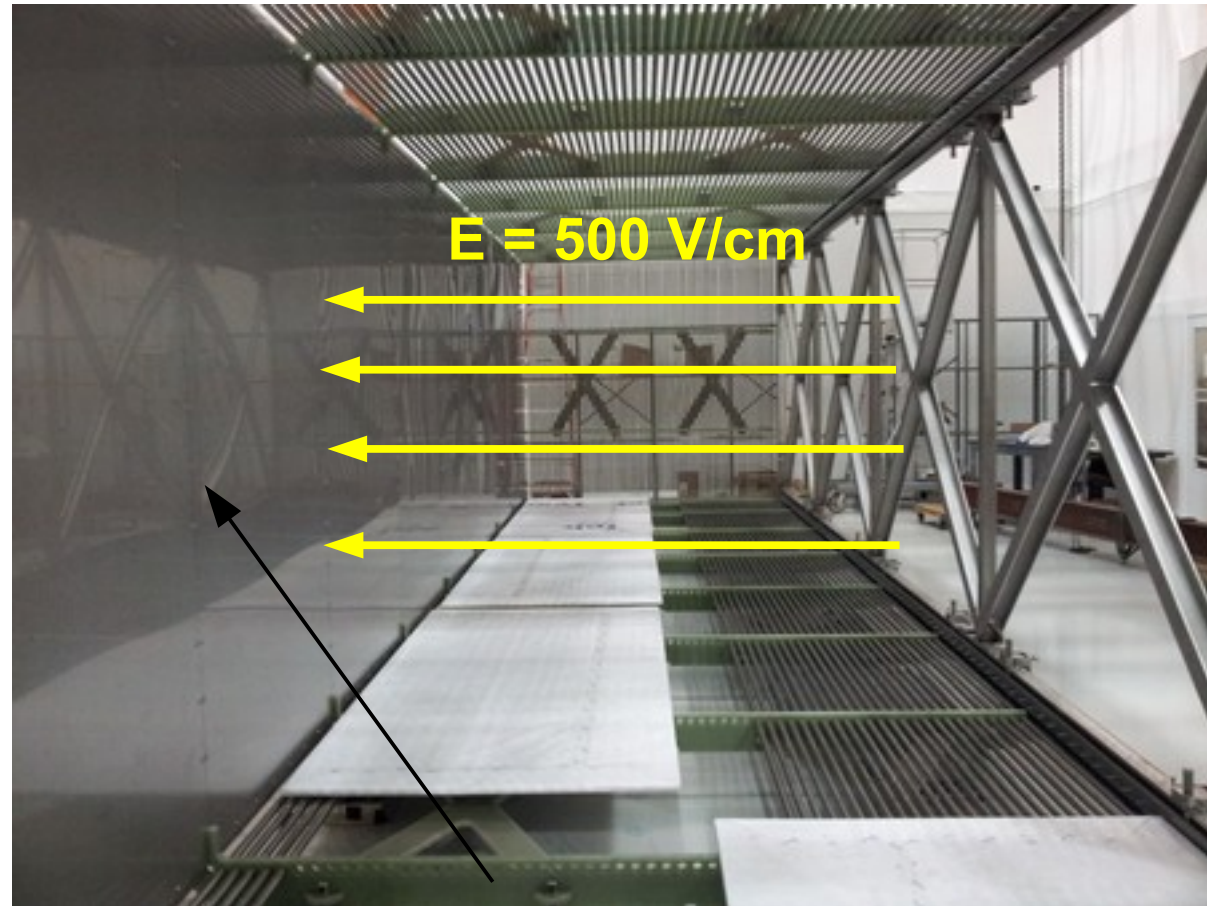
In fact this uniform electric field & the wires that read out the ionization charge is what makes up our Time Projection Chamber (TPC)

I will use the MicroBooNE TPC (the one I have most experience with) as my working example for how we build a time projection chamber

What are all these parts for?



Lets talk TPC



The goal is to get the maximum amount of charge possible drifted from where the interaction occurs over to the anode side (where the sense wires are)

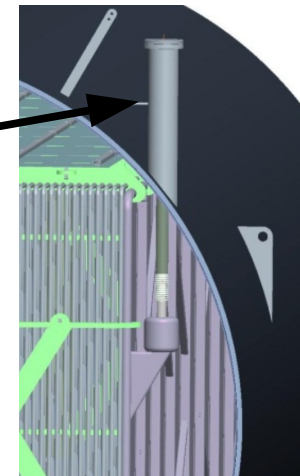
This can only be obtained if you have a very uniform electric field inside your TPC

To achieve this uniform field we start with a very flat cathode plane that we bring to -128 kV

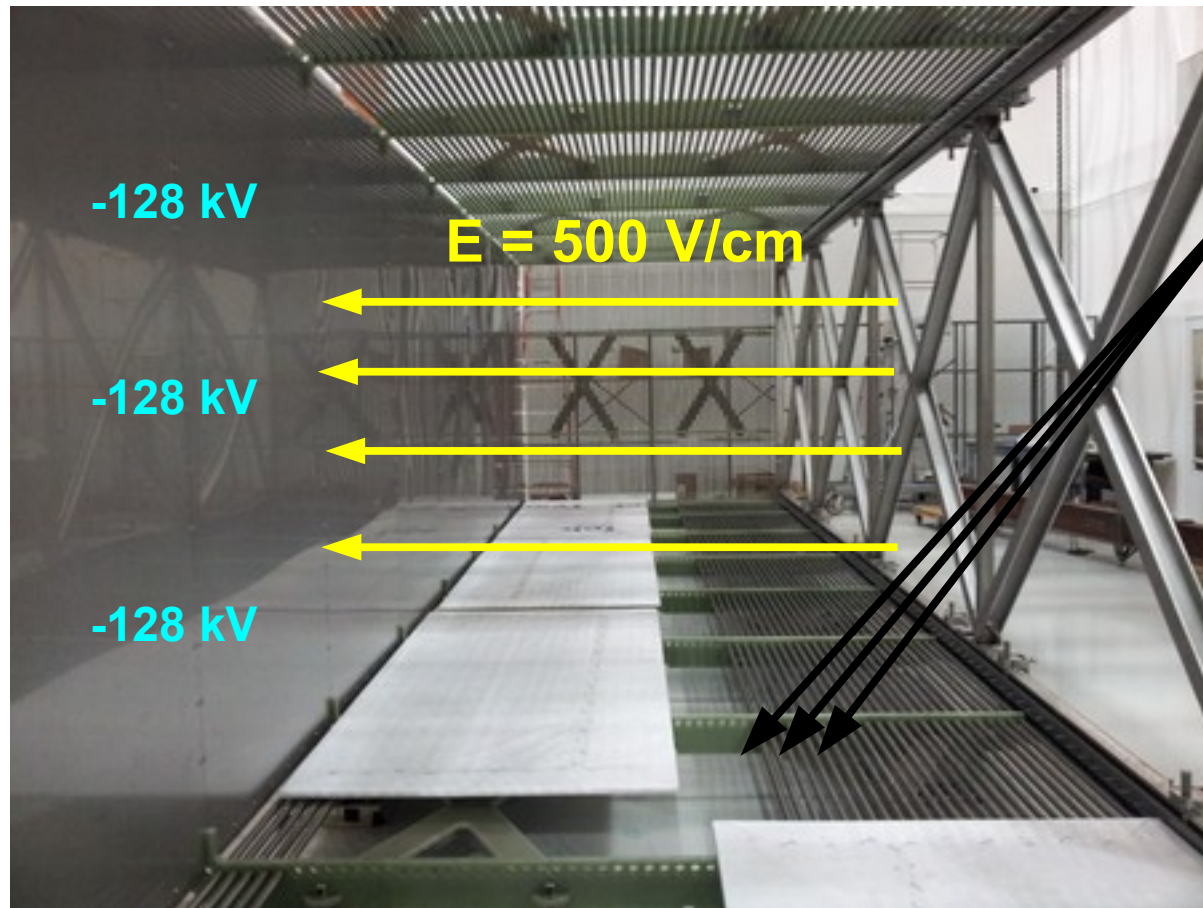


We use a special High Voltage feed through to deliver this bias

Shown here schematically

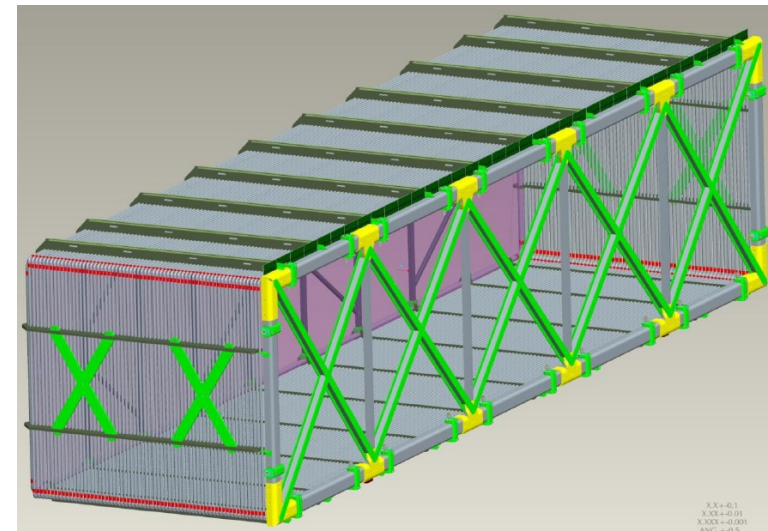


Lets talk TPC

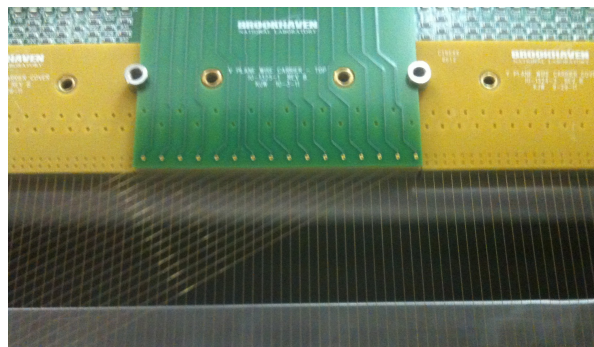
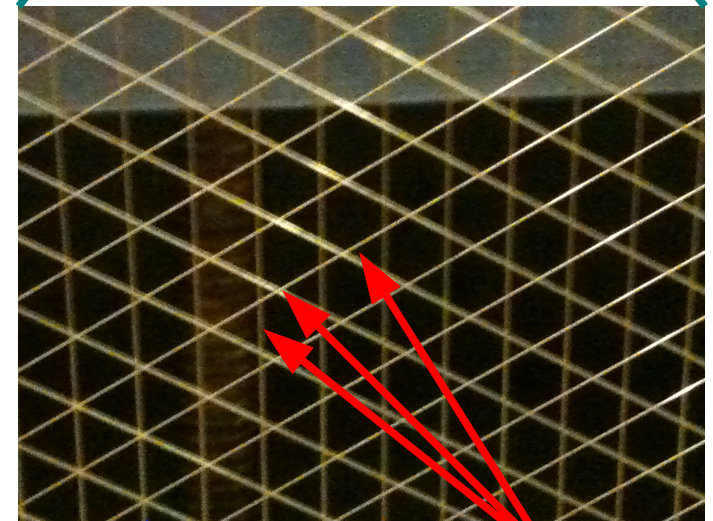
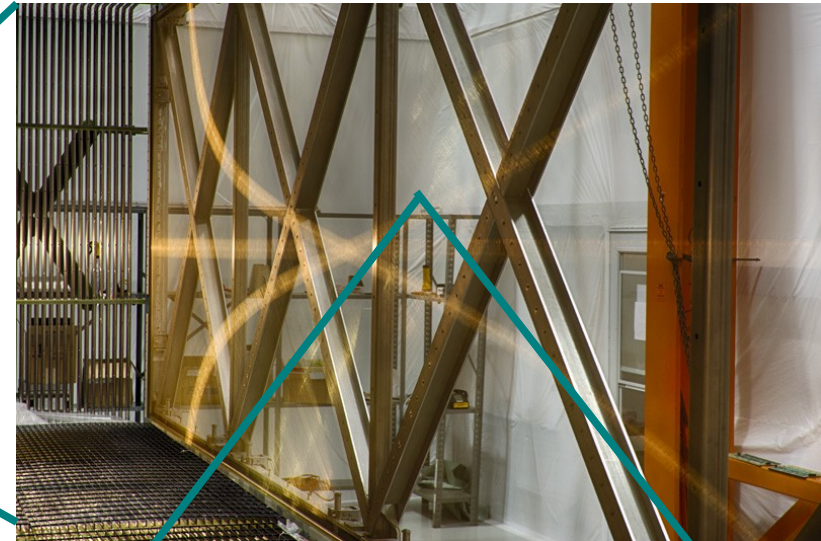
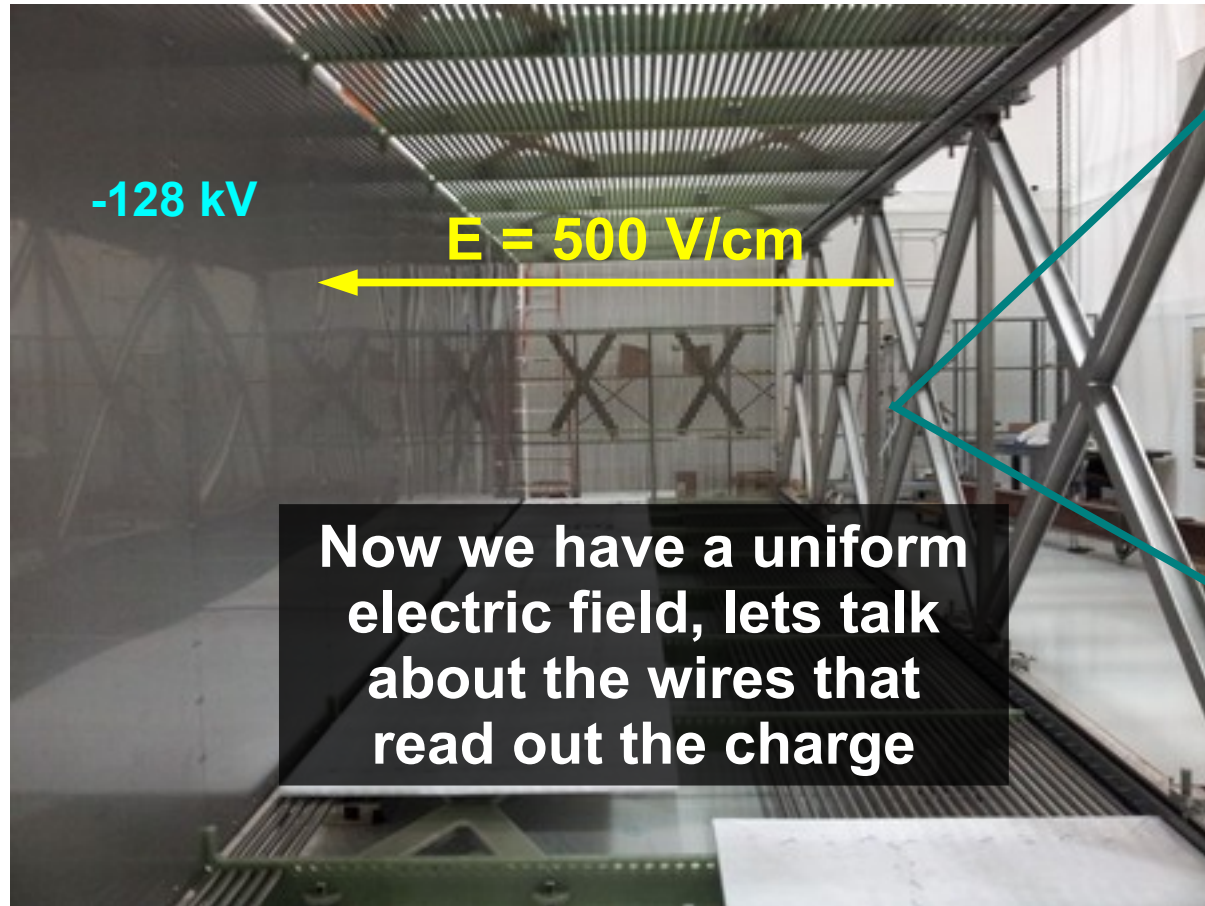


Once fully assembled, we will have the field cage tubes running in continuous bands around the TPC spaced uniformly a few (4.0 cm) centimeters apart

By attaching a series of resistors (250 M Ω) from one field cage tube to the next, we slowly step up the electric field (2kV steps) from the cathode side to the anode side while maintaining a field that is very uniform



Lets talk TPC



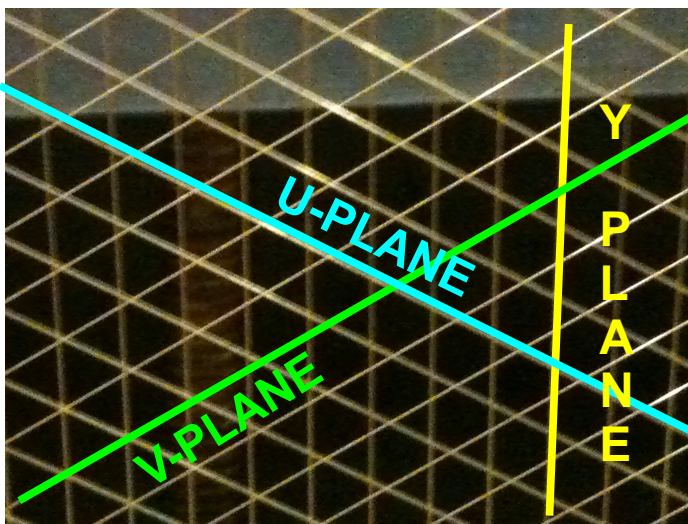
Two of the three wire planes during installation

MicroBooNE uses 3 wire planes. One vertical (Y-plane) and two diagonal (U, and V plane) at $\pm 60^\circ$

3 mm wire spacing

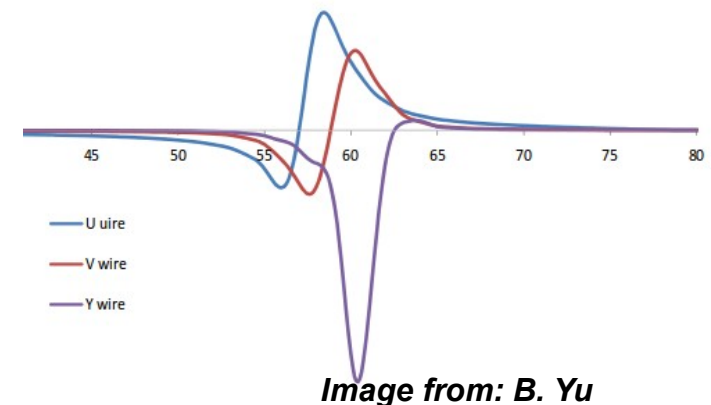
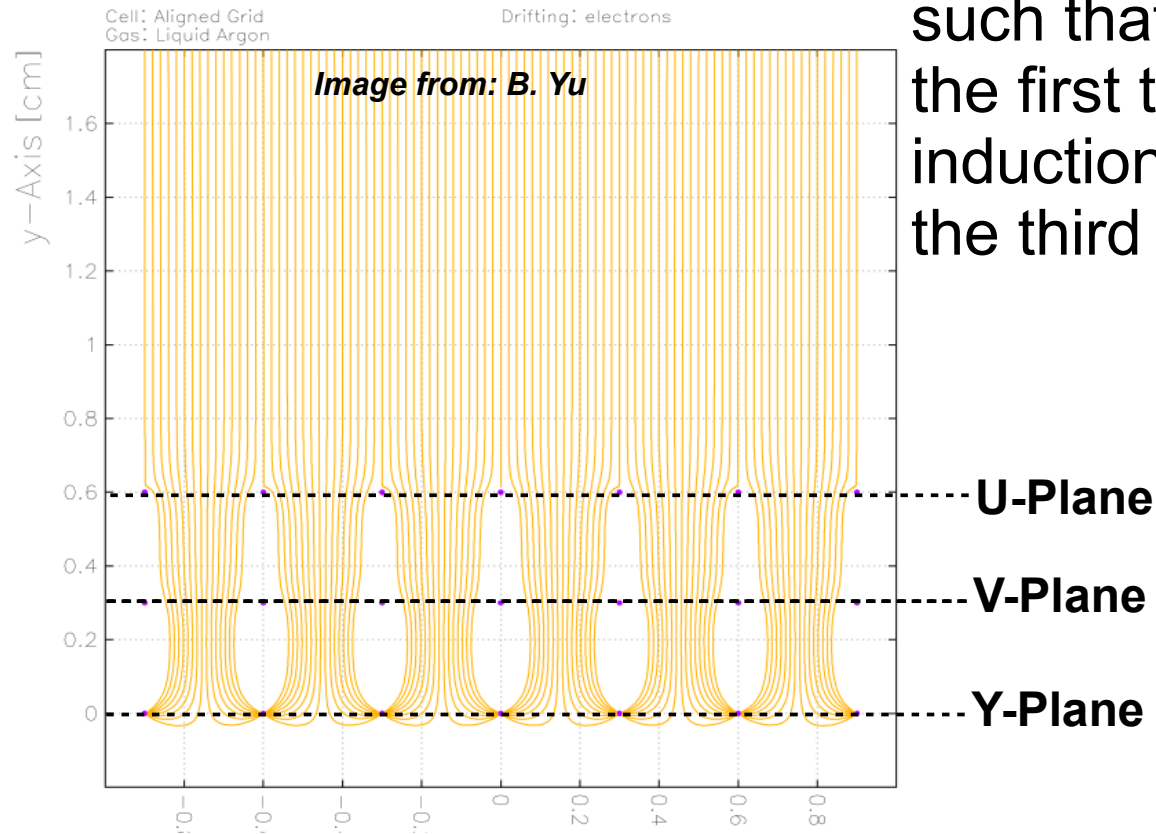
3 mm plane to plane spacing

A little more about wires

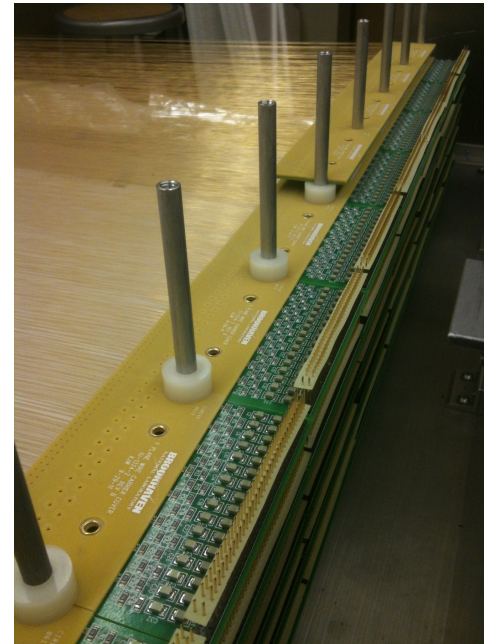
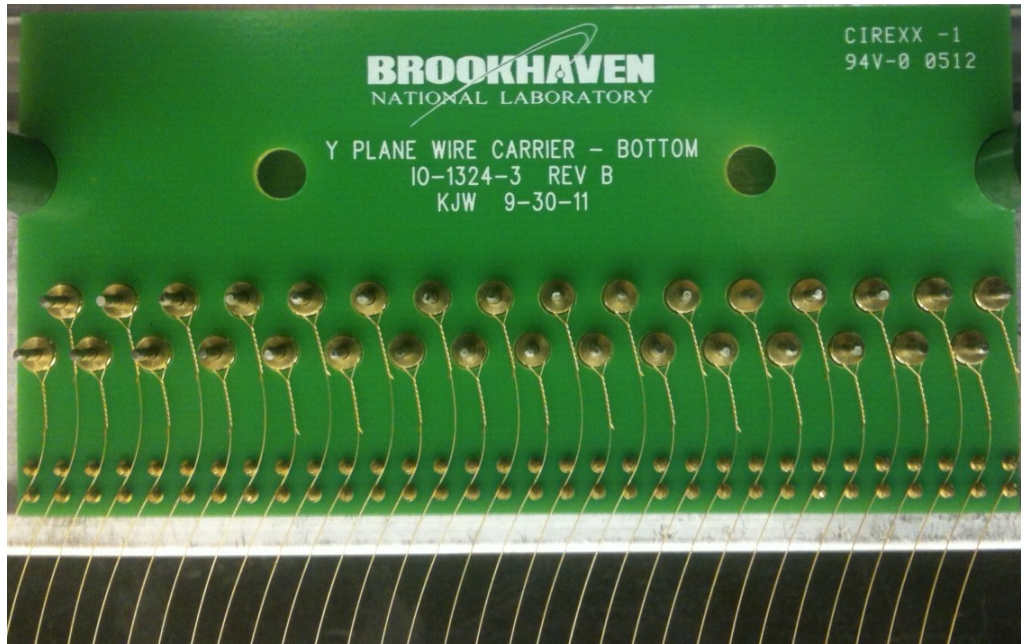


You will often hear people talk about the three planes of wires as being two induction planes and one collection plane

What we mean is that we've configured the electric field near the wire planes (meaning we've biased the wire planes) such that the drifting charge passes by the first two wire planes (creating an induction pulse) and then collects on the third wire plane



A little more about wires

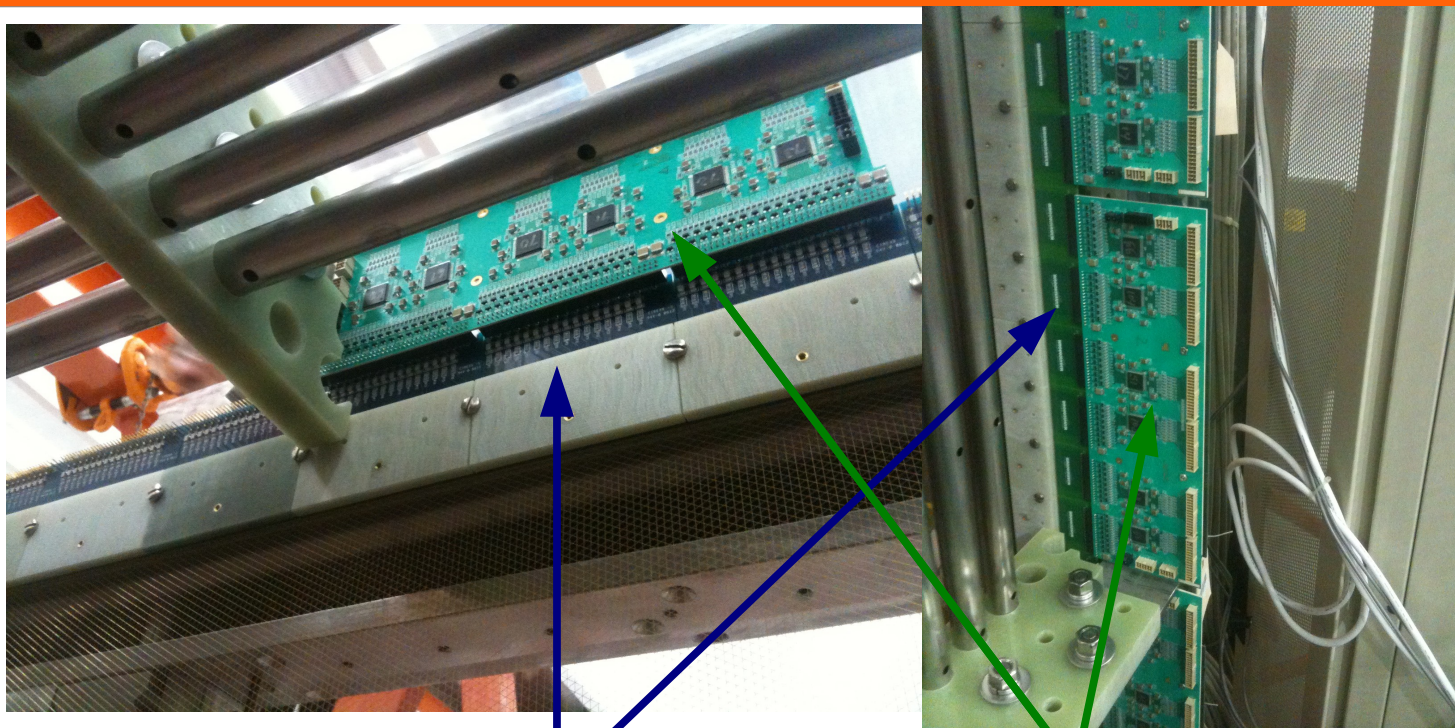


In MicroBooNE all **8256 wires** were placed **one-by-one** on wire carrier boards

These wire carrier boards have resistors and capacitors on each channel that allow us to read off the charge collected collected (either by induction or collection) on every wire

Remember: All of this is happening inside the liquid argon (@ 87° K), so we need special “cold” electronics that attach to the wire carrier board to take the charge collected and turn it into a signal we read out

Cold Electronics



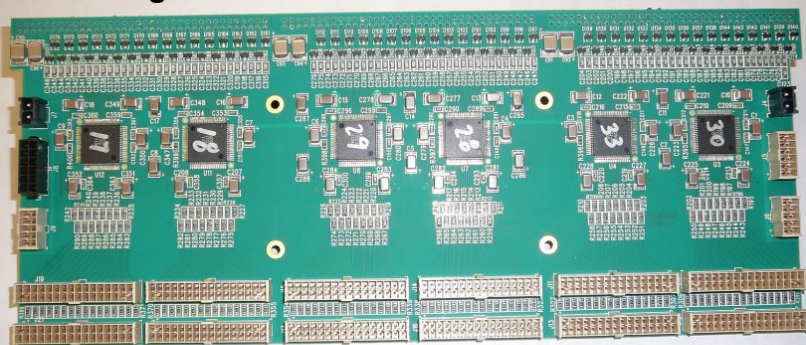
Wire carrier board

Cold Motherboard

These cold electronics pre-amplifiers will be placed inside a LArTPC cryostat

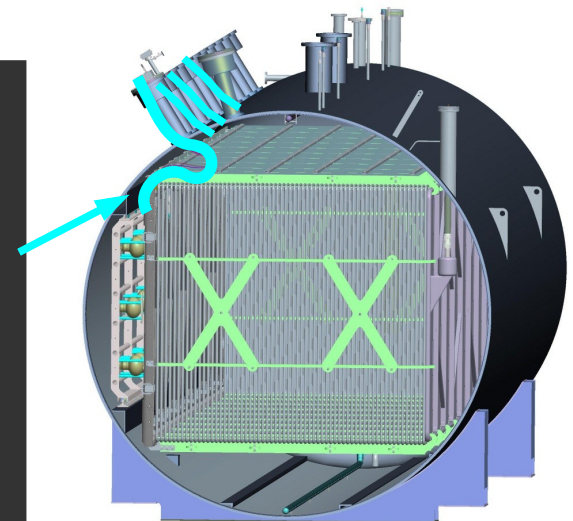
This is a necessary step since in large detectors transmitting a small signal over a long distance is very difficult

Image from: H. Chen

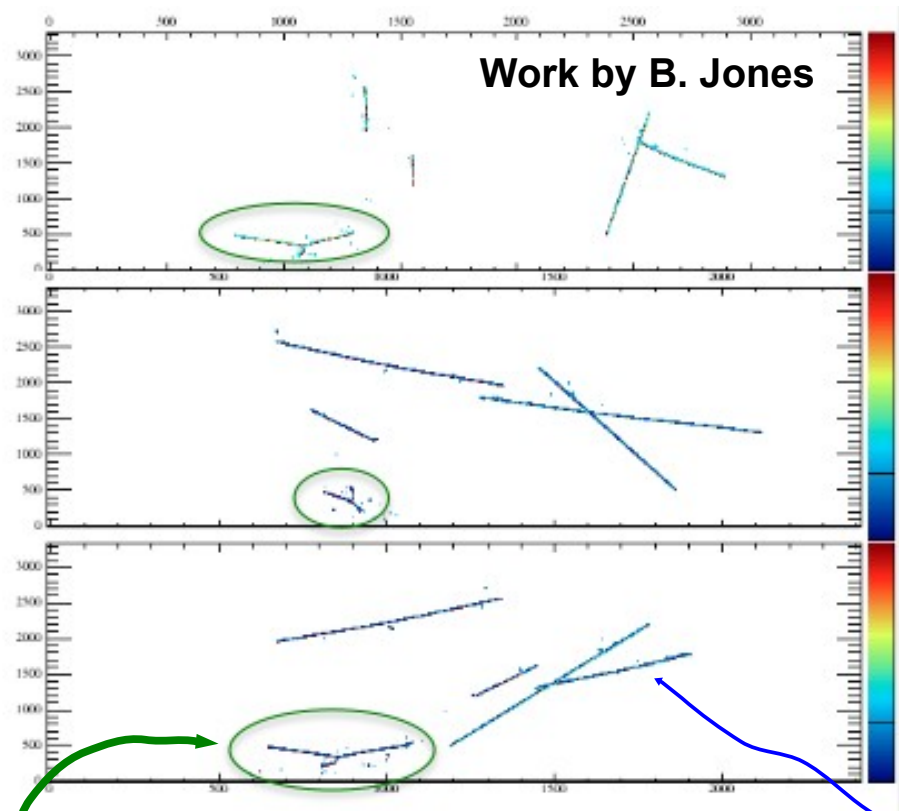


2nd Cold Mother Board with 12 ASICs populated

Now special cryogenic cables (cold cables) take the pre-amplified signal from the motherboards and carries this out of the cryostat

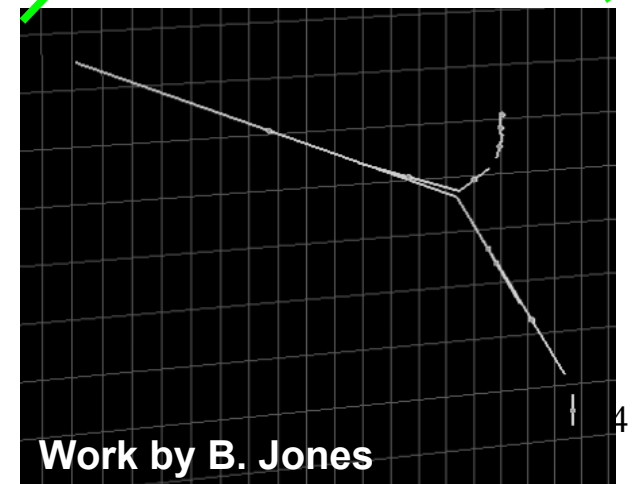
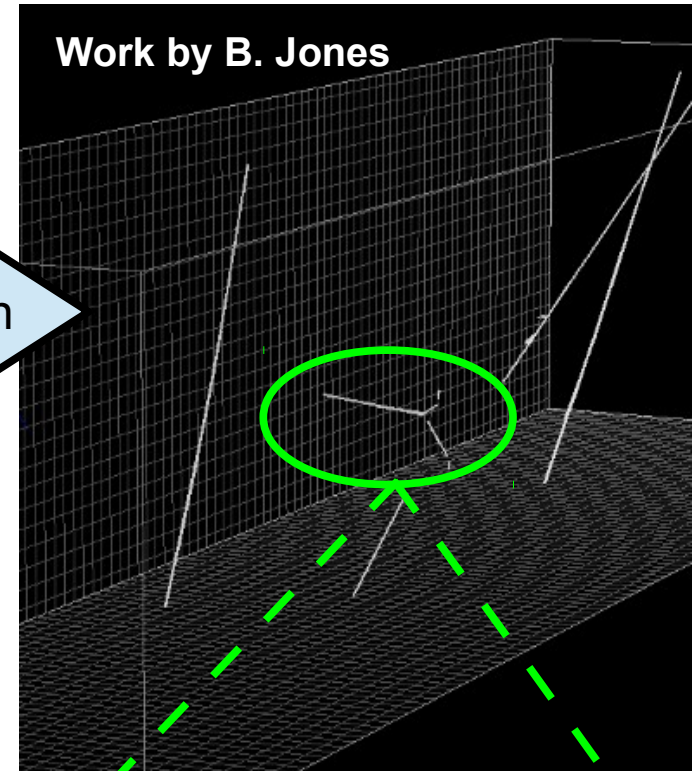


3-d reconstruction in MicroBooNE (Monte Carlo...for now)



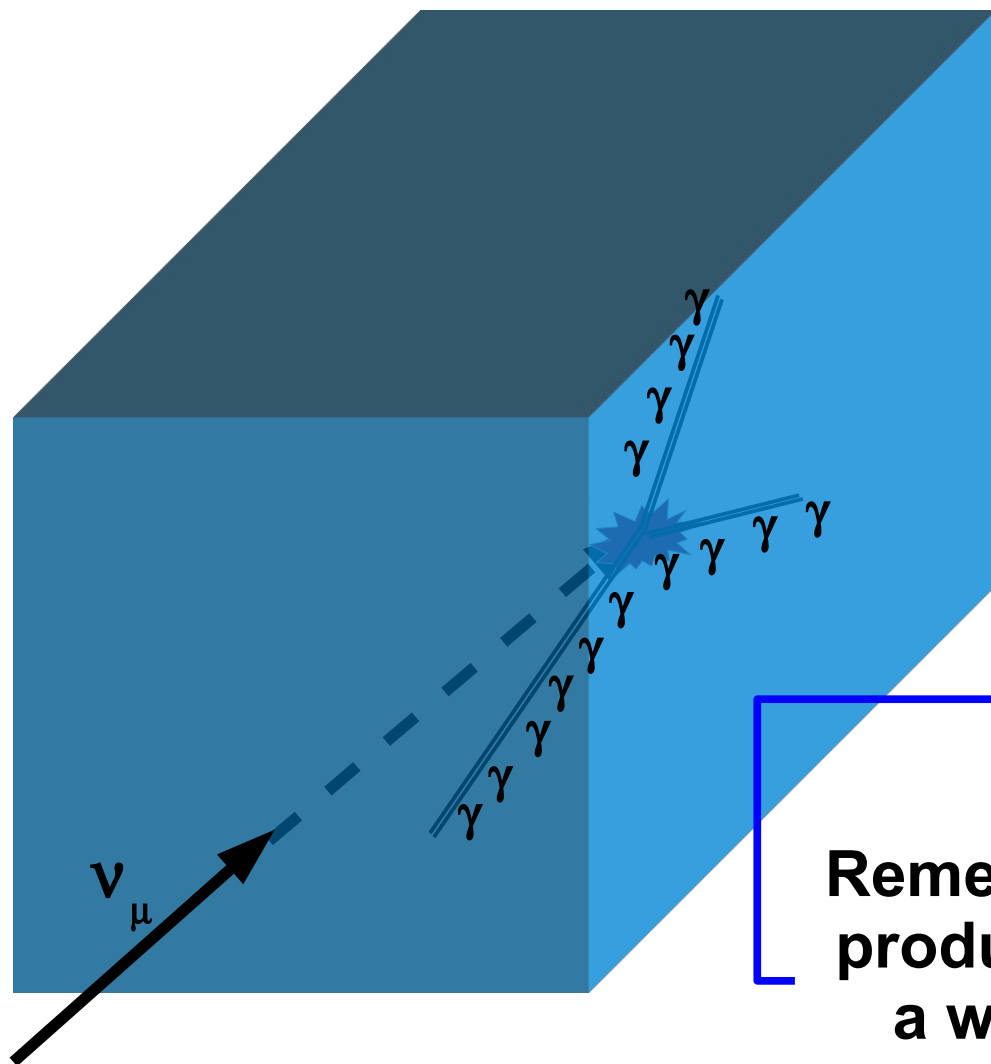
Simulated data in MicroBooNE with
neutrino interactions and **cosmic rays**
seen in each 2-d wire plane


3d-Reconstruction



This is a 3d reconstruction of simulated data and electronics in the MicroBooNE detector showing the amazing resolution we can achieve with this detector

Light detection too!!

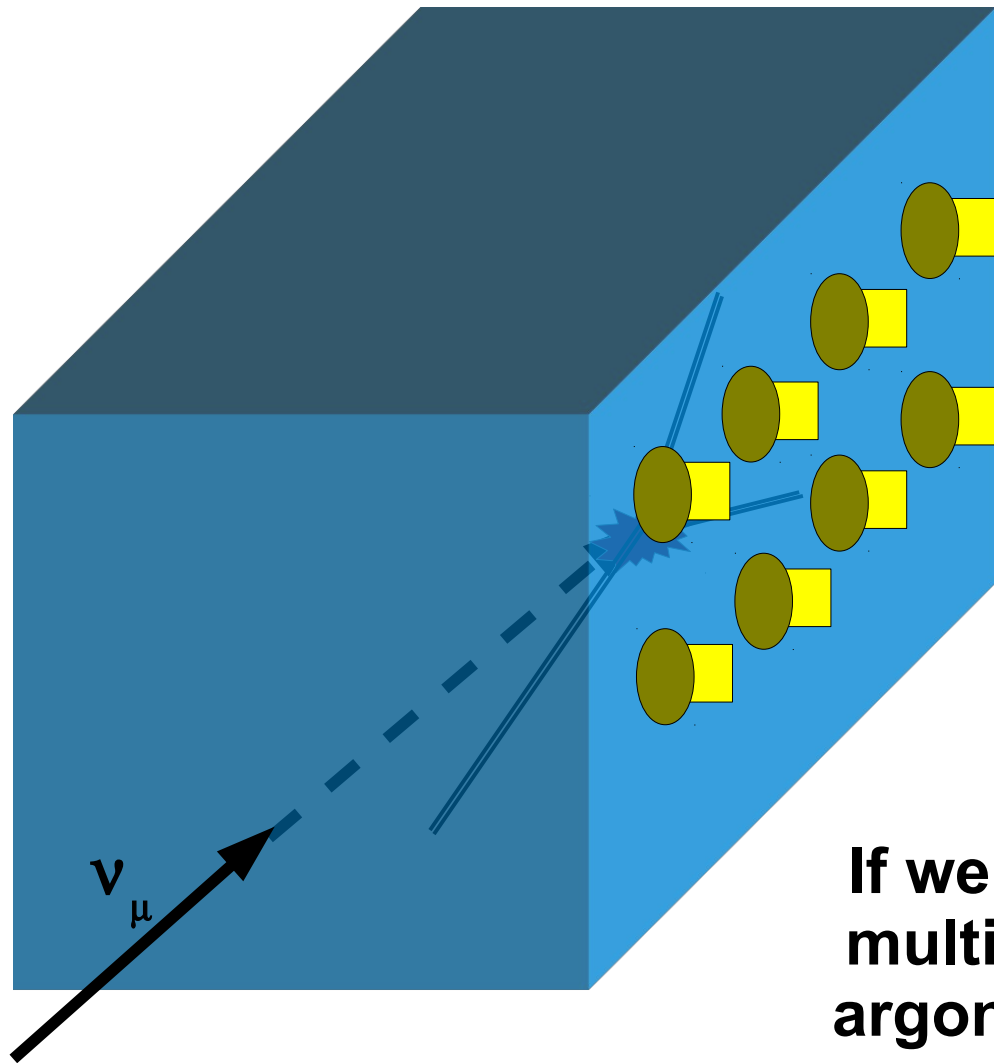


| | |
|---|--------|
|  | |
| Boiling Point [K] @ 1 atm | 87.3 |
| Density [g/cm ³] | 1.4 |
| Radiation Length [cm] | 14.0 |
| dE/dx [MeV/cm] | 2.1 |
| Scintillation [γ /MeV] | 40,000 |
| Scintillation λ [nm] | 128 |

Remember that we also liked that LAr produced a lot of scintillation light at a wavelength (128nm \rightarrow UV light) argon was transparent to.

So how do we capitalize on this wealth of information?!

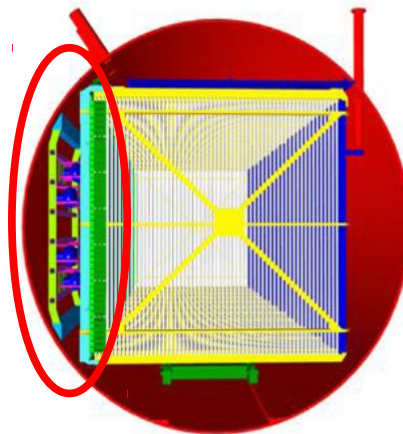
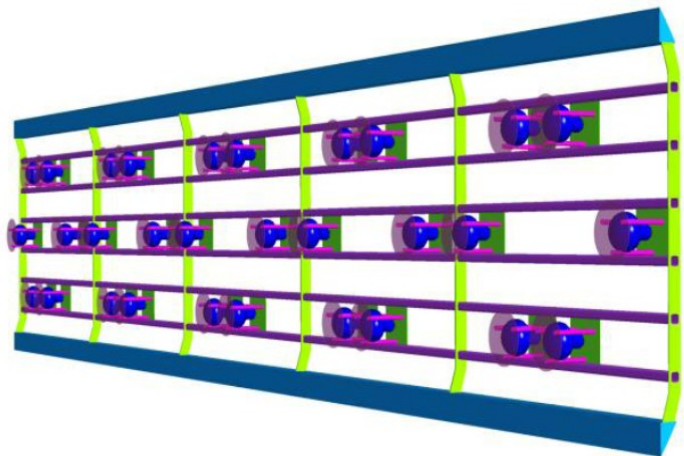
Light detection too!!



| | |
|--------------------------------|--------|
| Ar | |
| Boiling Point [K] @ 1 atm | 87.3 |
| Density [g/cm ³] | 1.4 |
| Radiation Length [cm] | 14.0 |
| dE/dx [MeV/cm] | 2.1 |
| Scintillation [γ /MeV] | 40,000 |
| Scintillation λ [nm] | 128 |

If we place a large number of photomultiplier tubes (PMT's) in the liquid argon we can utilize the light readout to give us spatial and time information about the interaction in the argon

Light detection too!!



We place 30'ish cryogenic PMT's behind the wire planes spatially distributed down the length of the TPC

I am not an expert in light detection and if you want to know more you should talk to Ben Jones, Teppei Katori, and Matt Toups (There is a lot of information and work in this system)



PMT mounted in the TPC

However, it isn't quite as simple as sticking a PMT in a cryogenic environment!

For one thing, PMT's are sensitive to visible light and the light produced in argon is UV...so we use these plates coated with a special wavelength shifting²⁷ material (TPB)

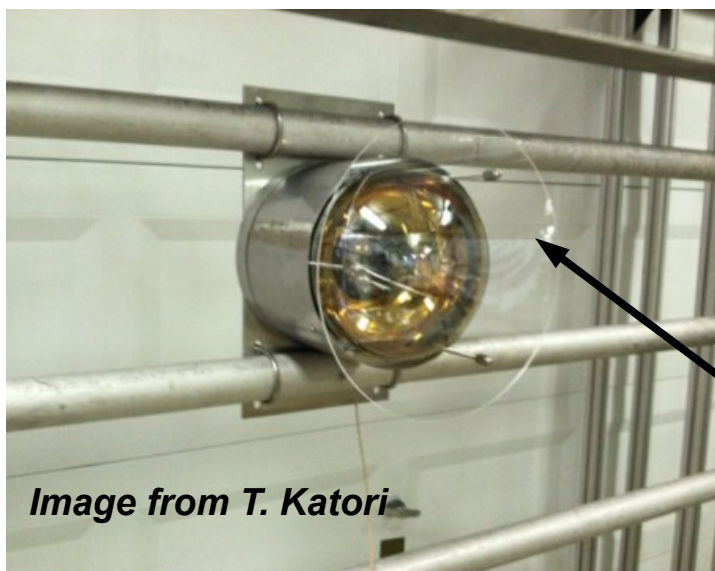
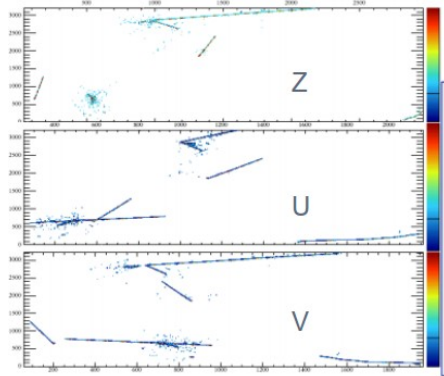


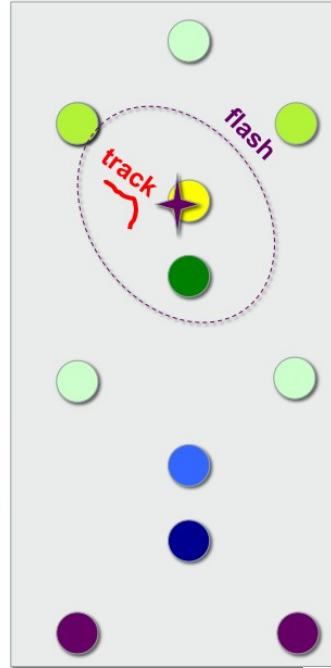
Image from T. Katori

Light detection too!!

Image from B. Jones

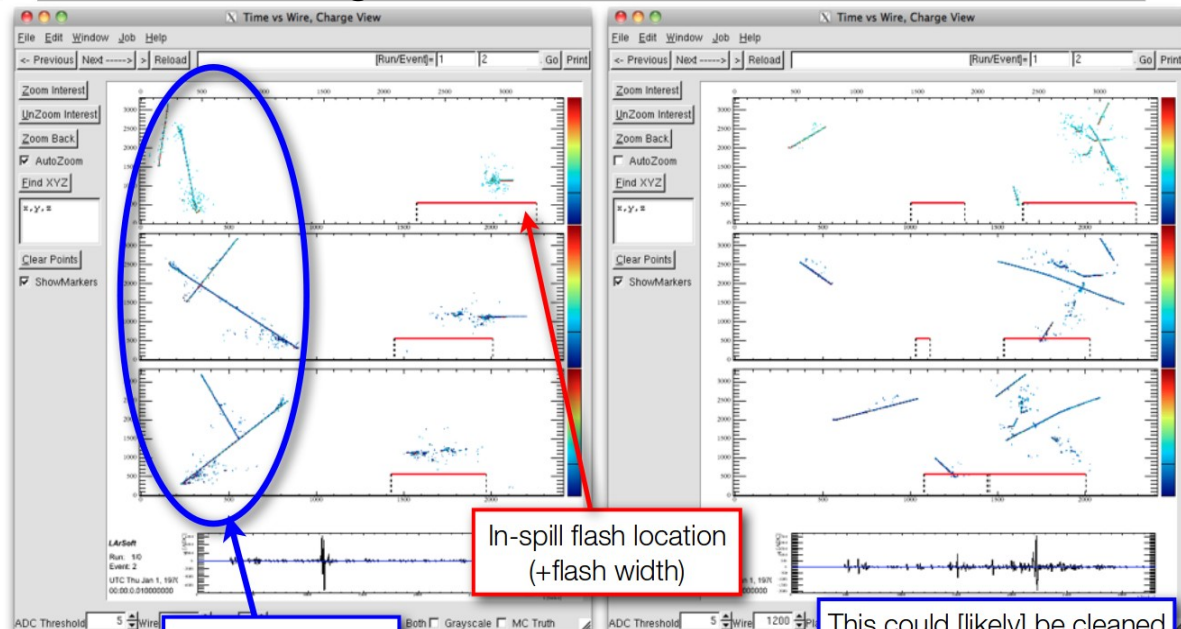


Cartoon:



By using the geometric distribution of the light found in the PMT's we can begin to distinguish between neutrino events in our detector and other activity (cosmic rays)

Image from S. Lockwitz & B. Jones



In-spill flash location
(+flash width)

Great, we can just
ignore this area

This could [likely] be cleaned
up with additional methods

Liquid Argon Time Project Chamber

Unfortunately I haven't even really scratched the surface of all the interesting aspects, challenges, and research that goes into LArTPC's

→ Purity

- How pure do we need the LAr to be (answer is really pure)
- How do we achieve this purity (cryogenic filters & recirculation)
- How to fill a large volume with pure LAr without pumping out a huge vacuum
- How do we monitor the purity

→ Cryogenics

- How do we re-condense argon that has boiled off to a gas
- How do we circulate a liquid at 87°K
- How do we monitor the cryogenic system

→ Electron Mobility and Recombination

- The electron drift distance is effected by the purity of the LAr
- How do electrons re-combine with the positive ions in the event

→ Particle ID

- Now that we have this incredible resolution in a neutrino detector, how well can we identify everything we see
- How sensitive are we to low energy events in LAr
- What can we learn about the nuclear physics of a neutrino Interaction

→ Light Detection

- There was literally a 3 day long conference dedicated to this At Fermilab, so yeah there is a lot here!

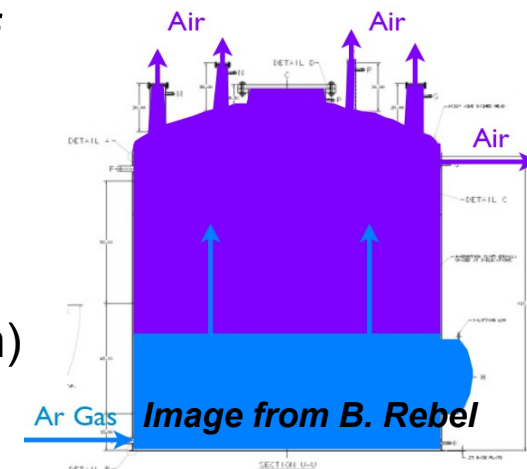
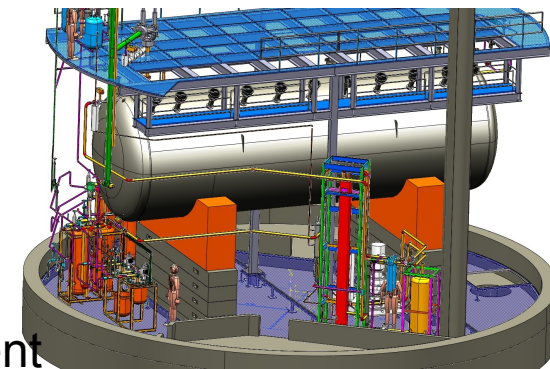


Image from J. Raaf



**Thank you very much
for your attention!**

